DEVELOPMENT OF A MATHEMATICAL MODEL TO PREDICT LONGITUDINAL TRACTOR STABILITY

by

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Introduction

The original question that prompted this study was, "What are the conditions that would cause a conventional two wheel drive tractor to tip over backwards and how could these conditions of instability be predicted?" Tractor stability is a very serious safety problem when the operator is using the tractor with high draft loads and operating on relatively steep slopes. A mathematical means of analyzing the parameters that affect tractor stability would allow the design engineer the opportunity to study affects of the actual design of the tractor and the implement on the stability of the tractor. The design engineer could then try to maximize stability by utilizing the optimum stability designs of the tractor and implements that were obtained from the mathematical analysis. An even more ideal solution to the problem of operator safety would be the installation of many electronic sensing devices on the tractor that would sense all of the necessary parameters involved with stability. All of these sensors could then be connected to a minicomputer using the relatively new silicon chips to cheaply analyze the constantly varying input conditions and calculate whether or not the tractor is stable. Such a system would allow total operator safety and would be able to accurately predict stability regardless of the conditions the tractor was operating in. The possibility that new regulations concerning operator safety will soon be invoked is a very real possibility and a study such as the author is undertaking should help to more closely define the problems involved with determining tractor stability and also should allow the engineer to get an idea of how the various parameters affect tractor stability.

Objectives

The main objective of this study was to determine all of the parameters affecting longitudinal tractor stability and to develop a simple mathematical model that could analyze and predict tractor stability for various tractor and implement designs.

Review of Literature

One of the first important parameters that was encountered in this study was the amount of drawbar pull that a particular tractor could generate. Drawbar pull was dependent on the amount of power that the tractor had available and was also dependent on the type of hitch and soil conditions the tractor was operating in. Mr. Frank Zoz developed a means of predicting tractor performance on soils while he was working as an engineer for John Deere.[3] Zoz based his solution on the following free body diagram of the tractor:

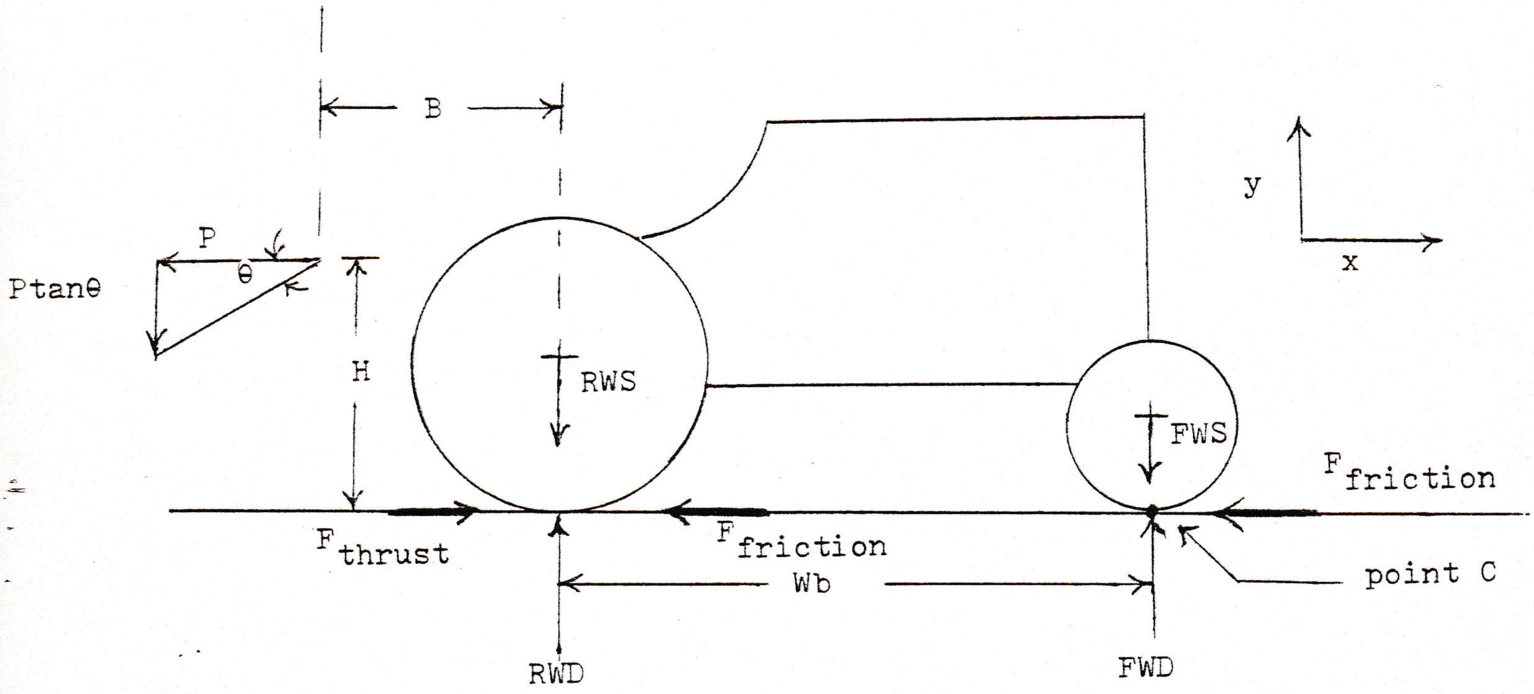


Figure 1. Zoz's Free Body Diagram

The variables that Zoz used were defined as follows:

P = the horizontal component of the pull exerted on the tractor by the implement

$P\tan\theta$ = the vertical component of the pull exerted on the tractor by the implement

θ = the angle of pull with respect to the horizontal

H = vertical distance from the ground to the point of application of the pull

B = horizontal distance from the center of the rear axle of the tractor to the point of application of the pull

F_{thrust} = the thrust force exerted on the soil by the tractor tire which acts to propel the tractor forward

RWS = rear weight static(Zoz divided the static weight of tractor into two components acting at the centers of the rear and front wheels respectively)

RWD = rear weight dynamic, the vertical reaction of the soil on the tractor in the dynamic state

$F_{friction}$ = forces of friction of the soil acting on the tires

Wb = wheelbase of the tractor

FWS = front weight static

FWD = front weight dynamic

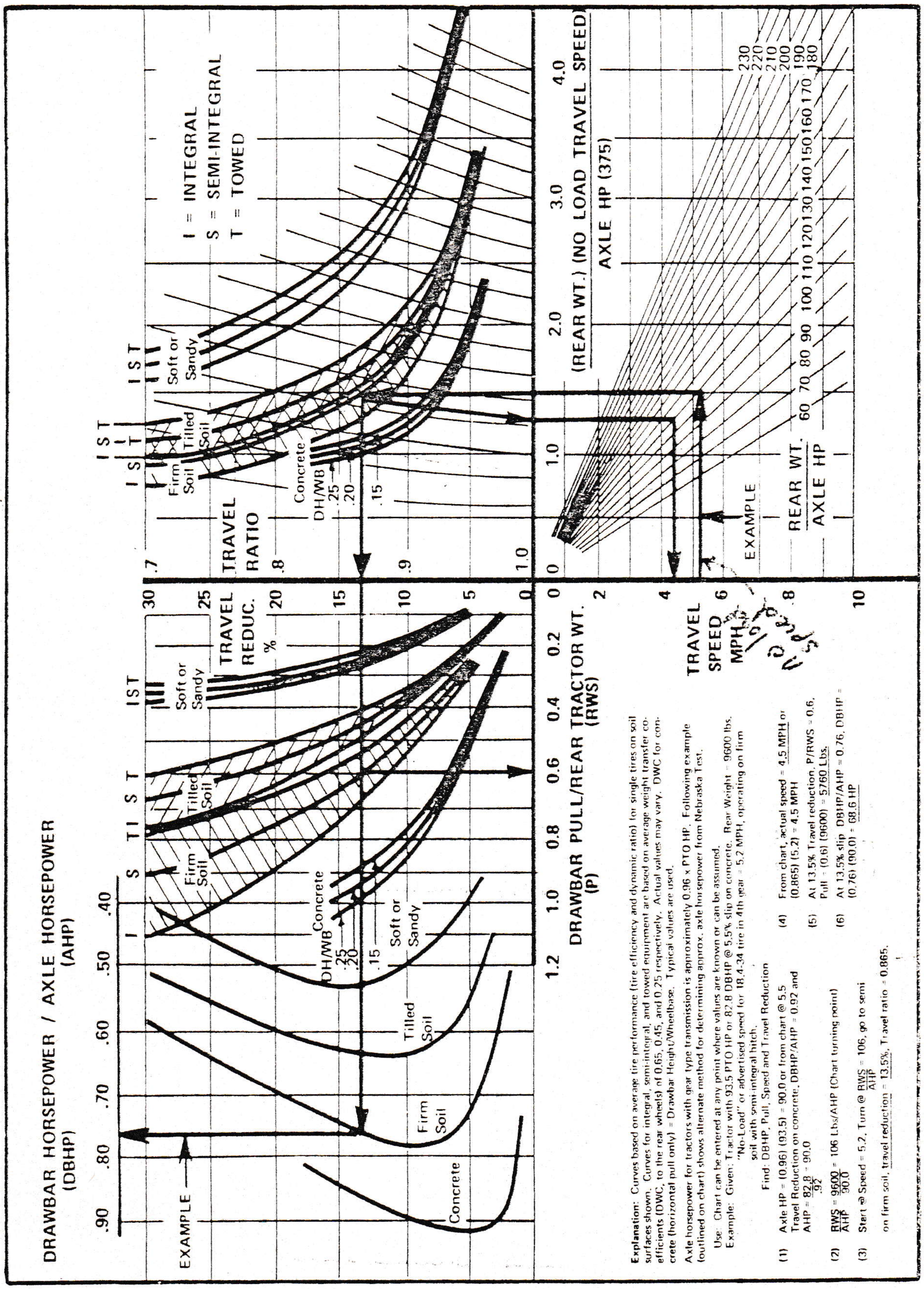
The first step in Zoz's analysis was to sum the moments around point C because this conveniently eliminated the thrust force and the friction forces which are very difficult quantities to predict and measure. Summing the moments around point C gave:

$$\sum M_c = 0 = RWS\cdot Wb - RWD\cdot Wb + P\cdot H + P\tan\theta(Wb + B)$$

$$\left[RWD\cdot Wb = RWS\cdot Wb + P\cdot H + P\tan\theta(Wb + B)\right]\frac{1}{Wb}$$

$$RWD = RWS + P\left[\frac{H}{Wb} + \tan\theta\left(1 + \frac{B}{Wb}\right)\right]$$

This equation could not be evaluated directly because the location of the point of application of the pull defined by H, B, and the angle theta was not known for integral and semi-integral type hitches. Zoz solved this problem by first calling the term $\frac{H}{Wb} + \tan\theta\left(1 + \frac{B}{Wb}\right)$ the Dynamic Weight Coefficient. Zoz then performed many field tests with different tractors and different hitches and arrived at three values of DWC. He determined that the value of DWC was approximately .65 for an integral hitch, .45 for a semi-integral hitch, and .25 for a towed implement. Zoz used this equation for the basis of his work and coupled with a lot of testing and research work he was able to arrive at a simple traction chart that could predict tractor performance with a relatively high degree of correllation between his predicted results and actual measured results. Zoz's chart was designed with the idea that an engineer or a consumer could use the Nebraska Tractor Test results to easily compare and predict performance of any type of tractor operating with different types of hitches in different types of soils. Zoz's chart was relatively easy to understand and was given in the following form:



Explanation: Curves based on average tire performance (tire efficiency and dynamic ratio) for single tires on soil surfaces shown. Curves for integral, semi-integral, and towed equipment are based on average weight transfer coefficients (DWC, to the rear wheels) of 0.65, 0.45, and 0.25 respectively. Actual values may vary. DWC for concrete (horizontal pull only) = Drawbar Height/Wheelbase. Typical values are used.

Axle horsepower for tractors with gear type transmission is approximately 0.96 x PTO HP. Following example (outlined on chart) shows alternate method for determining approx. axle horsepower from Nebraska Test.

Use: Chart can be entered at any point where values are known or can be assumed.
Example: Given: Tractor with 93.5 PTO HP or 82.8 DBHP @ 5.5% slip on concrete. Rear Weight = 9600 lbs. "No-Load" or advertised speed for 18.4-34 tire in 4th gear = 5.2 MPH, operating on firm soil with semi-integral hitch.
Find: DBHP, Pull, Speed and Travel Reduction

(1) Axle HP = (0.96) (93.5) = 90.0 or from chart @ 5.5 Travel Reduction on concrete, DBHP/AHP = 0.92 and AHP = $\frac{82.8}{.92}$ = 90.0

(2) $\frac{\text{RWS}}{\text{AHP}} = \frac{9600}{90.0}$ = 106 Lbs/AHP (Chart turning point)

(3) Start @ Speed = 5.2, Turn @ $\frac{\text{RWS}}{\text{AHP}}$ = 106, go to semi on firm soil, travel reduction = 13.5%, Travel ratio = 0.865.

(4) From chart, actual speed = 4.5 MPH or (0.865) (5.2) = 4.5 MPH

(5) At 13.5% Travel reduction, P/RWS = 0.6, Pull = (0.6) (9600) = 5760 Lbs.

(6) At 13.5% slip DBHP/AHP = 0.76, DBHP = (0.76) (90.0) = 68.6 HP

Figure 2. Zoz's Traction Chart

Zoz's traction chart with its graphs of performance was an excellent tool, but to be used in a computer program the graphs must be fitted to mathematical equations that allow the computer to predict tractor performance. Professor D. R. Hunt, at the University of Illinois, developed the mathematical equations by using a computer to find the best equations to fit the curves.[2] Hunt was able to develop equations that fit these curves very accurately and they evolved into the following forms:

$$TE = \frac{-(A \cdot S + C) + \sqrt{(A \cdot S + C)^2 - 4(B \cdot S^2 + D \cdot S + E)}}{2}$$

TE = the tractive efficiency, decimal

S = drive wheel slip, decimal

	A	B	C	D	E
concrete	5.124	6.556	-1.596	-5.376	.6450
firm soil	6.928	12.00	-1.129	-7.749	.3895
tilled soil	6.928	12.00	-.7369	-7.355	.2375
sand	8.000	16.00	-.2280	-8.772	.1812

$$Slip = A - \sqrt{A^2 - \frac{DB\ Pull}{B\ SRAW}}$$

Slip = drive wheel slip, decimal

DB Pull = drawbar pull(same units as SRAW)

SRAW = static rear axle weight of tractor(same units as DB Pull)

	concrete			firm	
	A	B		A	B
R = .25	.165	37.85	int.	.388	7.77
R = .20	.166	35.81	semi-	.333	8.23
R = .25	.166	34.12	towed	.300	8.45

	tilled		sand	
	A	B	A	B
int.	.348	6.31	.303	4.12
semi-	.321	6.40	.313	3.62
towed	.322	5.69	.297	3.71

R = ratio of the drawbar height to the wheelbase in a concrete operating condition

Another important parameter that was soon encountered was the radius of the front and the rear wheels. For the sake of simplicity and availability of data, it was assumed that the dynamic loaded radius of the tires was approximately equal to the static loaded radius of the tires. The static loaded radius of most common tractor tires has been found by many sources and this information was used in the computer program so the user of the program could simply plug in the nominal tire size and the computer would match it up with the appropriate radius. The following values of static loaded radius' were used in the analysis:[1]

Drive Tires

Nominal tire size	Static loaded radius (inches)
9.5-16	15.2
18.4-16.1	19.5
8.3-24	18.2
9.5-24	19.0
11.2-24	19.0
12.4-24	20.8
13.6-24	21.5
14.9-24	22.4
16.9-24	23.1
13.6-26	22.6
14.9-26	23.4
16.9-26	24.1
18.4-26	25.6
23.1-26	27.7
28.1-26	27.9
11.2-28	21.9
12.4-28	22.8
13.6-28	23.5
14.9-28	24.4
16.9-28	25.1

Nominal tire size	Static loaded radius (inches)
18.4-28	26.7
14.9-30	25.5
16.9-30	26.1
18.4-30	27.4
23.1-30	29.9
24.5-32	31.5
16.9-34	28.1
18.4-34	29.4
23.1-34	32.0
13.9-36	26.9
11.2-38	26.9
13.6-38	28.6
15.5-38	28.6
16.9-38	30.4
18.4-38	31.6
20.8-38	32.8

Steering Tires

Nominal tire size	Static loaded radius (inches)
4.00-12	10.0
6.00-14	12.5
5.00-15	12.0

Nominal tire size	Static loaded radius (inches)
7.5-15	13.6
9.5-15	13.9
11-15	14.4
5.50-16	13.1
6.00-16	13.5
6.50-16	13.9
7.50-16	14.7
10.00-16	16.0
11.00-16	17.3
14-16.1	17.3
7.50-18	15.9
7.50-20	16.9
9.50-20	17.9

Development of a Mathematical Model

The first assumption that was made before any attempt of a mathematical equation was even made was to assume that the criterion for reaching the point of instability for the tractor was that this point was reached when the front wheel reaction, FWD, of the soil upon the wheel reached a value of zero. The tractor was really unstable before this point because even if there was some small amount of front wheel reaction, there might not have been enough soil friction force to allow the operator to turn the wheels and steer the tractor. Since it was not known for every tractor how much of a front wheel reaction was necessary to steer the tractor, it was arbitrarily assumed that the criterion for instability was that the front wheel reaction, FWD, equalled zero. This meant that an equation containing the term FWD was the desired result of this analysis in order to allow a calculation of FWD and a subsequent determination of the tractor's stability.

The first step in the development of the mathematics governing tractor stability was to develop a free body diagram of the tractor which showed all of the external forces acting upon the tractor. The following free body diagram was chosen to show all of the forces that were acting upon the tractor:

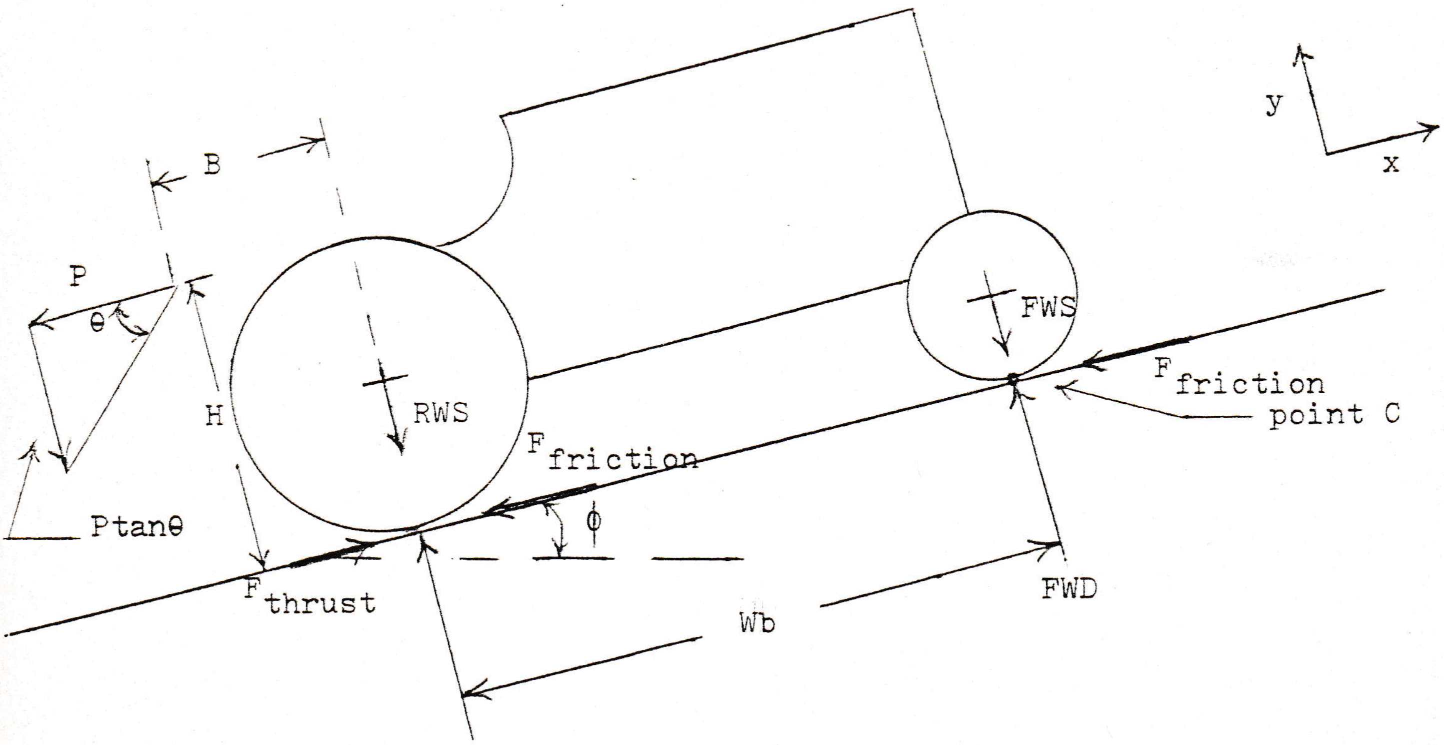


Figure 3. Free Body Diagram of Tractor on Slope

The variables that were used in the free body diagram were defined as follows:

P = the component of the pull exerted on the tractor by the implement that was parallel to the soil's surface

Ptanθ = the component of the pull exerted on the tractor by the implement that was perpendicular to the soil's surface

θ = the angle that the total pull made with the soil's surface

B = the distance from the center of the rear axle to the point of application of the pull that was measured in the direction parallel to the soil's surface

H = the distance from the soil's surface to the point of application of the pull that was measured in the direction perpendicular to the soil's surface

RWS = rear weight static, the component of the weight of the tractor that acted through the center of the rear axle and was perpendicular to the soil's surface

RWD = rear weight dynamic, the component of the soil's reaction upon the rear tire that was perpendicular to the soil's surface

ϕ = the angle of inclination of the soil's surface with respect to the horizontal direction

Wb = the wheelbase of the tractor

FWS = front weight static, the component of the weight of the tractor that acted through the center of the front axle and was perpendicular to the soil's surface

FWD = front weight dynamic, the component of the soil's reaction upon the front tire that was perpendicular to the soil's surface

The first step in analyzing the free body diagram was to sum the moments around point C:

$$\sum M_c = 0 = RWS*Wb + P\tan\theta(Wb + B) - RWD*Wb + P*H$$

Rearranging terms:

$$Wb*RWD = RWS*Wb + P\tan\theta(Wb + B) + P*H$$

$$RWD = RWS + P\left[\frac{H}{Wb} + \tan\theta\left(1 + \frac{B}{Wb}\right)\right]$$

This equation was identical to the equation that Zoz used for his work. Therefore the next step was to substitute DWC, a term whose value we knew, for $\frac{H}{Wb} + \tan\theta(1 + \frac{B}{Wb})$. This gave us the following expression:

$$RWD = RWS + P*DWC$$

The main objective of this analysis was to look for an equation that contained the term FWD and it was apparent that the above equation does not contain it, so the next step was to sum the forces in the y direction:

$$\sum F_y = 0 = FWD + RWD - P\tan\theta - RWS - FWS$$

Rearranging terms:

$$RWD = P\tan\theta + RWS + FWS - FWD$$

The above expression was an equation with the term FWD, but it also contained the term RWD which was a relatively unmeasurable quantity. RWD was eliminated by substituting into the equation obtained for RWD from summing the moments around point C:

$$RWD = RWS + P*DWC = P\tan\theta + RWS + FWS - FWD$$

Rearranging terms:

$$RWS + P*DWC = P\tan\theta + RWS + FWS - FWD$$

$$P*DWC = P\tan\theta + FWS - FWD$$

$$FWD = P\tan\theta + FWS - P*DWC$$

The main objective of this analysis had now been reached because the above expression was an equation that contained FWD as a function of P, θ, FWS, and DWC. It now became obvious that if a means could have been found to determine these four variables, it would have been possible to calculate FWD. DWC was a constant that was known if it was also known what type of hitch was being used because Zoz determined the values for DWC as shown below:

	Integral hitch	Semi-integral hitch	Towed
DWC	.65	.45	.25

The angle θ was not known and had to be determined or approximated in order to use the above equation. The first step was to examine the DWC term because it also contained theta:

$$DWC = \frac{H}{Wb} + \tan\theta\left(1 + \frac{B}{Wb}\right)$$

Solving for theta:

$$\theta = \tan^{-1} \frac{\left(DWC - \frac{H}{Wb} \right)}{1 + \frac{B}{Wb}}$$

It was not possible to evaluate this expression directly for theta because the location of the point of application of the pull which was defined by the two distances of H and B was not known. Zoz arbitrarily chose B as the horizontal distance of the location of the point of pull. He could have just as well chosen B equal to zero because only the vertical location of the line of pull was really important. If B was picked to be zero, then the equation was simplified because $\frac{B}{Wb}$ now equalled zero:

$$\theta = \tan^{-1} (DWC - \frac{H}{Wb})$$

It still was not possible to evaluate theta directly from this equation because the distance H was not known. H was defined as the distance from the soil's surface to the point of application of the pull that was measured in the direction perpendicular to the soil's surface. It was known from practical experience that most engineers designed tractors and implements so that the line of pull passed below the center of the rear axle because designers had learned that the higher the line of pull, the more unstable the tractor was. Therefore it was decided to limit the distance H to be between r_1 (the loaded rear tire radius) and zero because the line of pull also did not usually pass below the ground level either. From examining the effect of applying P in a high vs. a low position as in the diagram below, it was noted that the overturning moment $M^*P\tan\theta$, due to $P\tan\theta$, was the same regardless of position, but the overturning moment due to P was much greater in a high position vs. a low position due to the increased lever arm(moment J*P vs. moment G*P). It was decided to check the affect of varying H to see exactly what affect it did have on the tractor's stability.

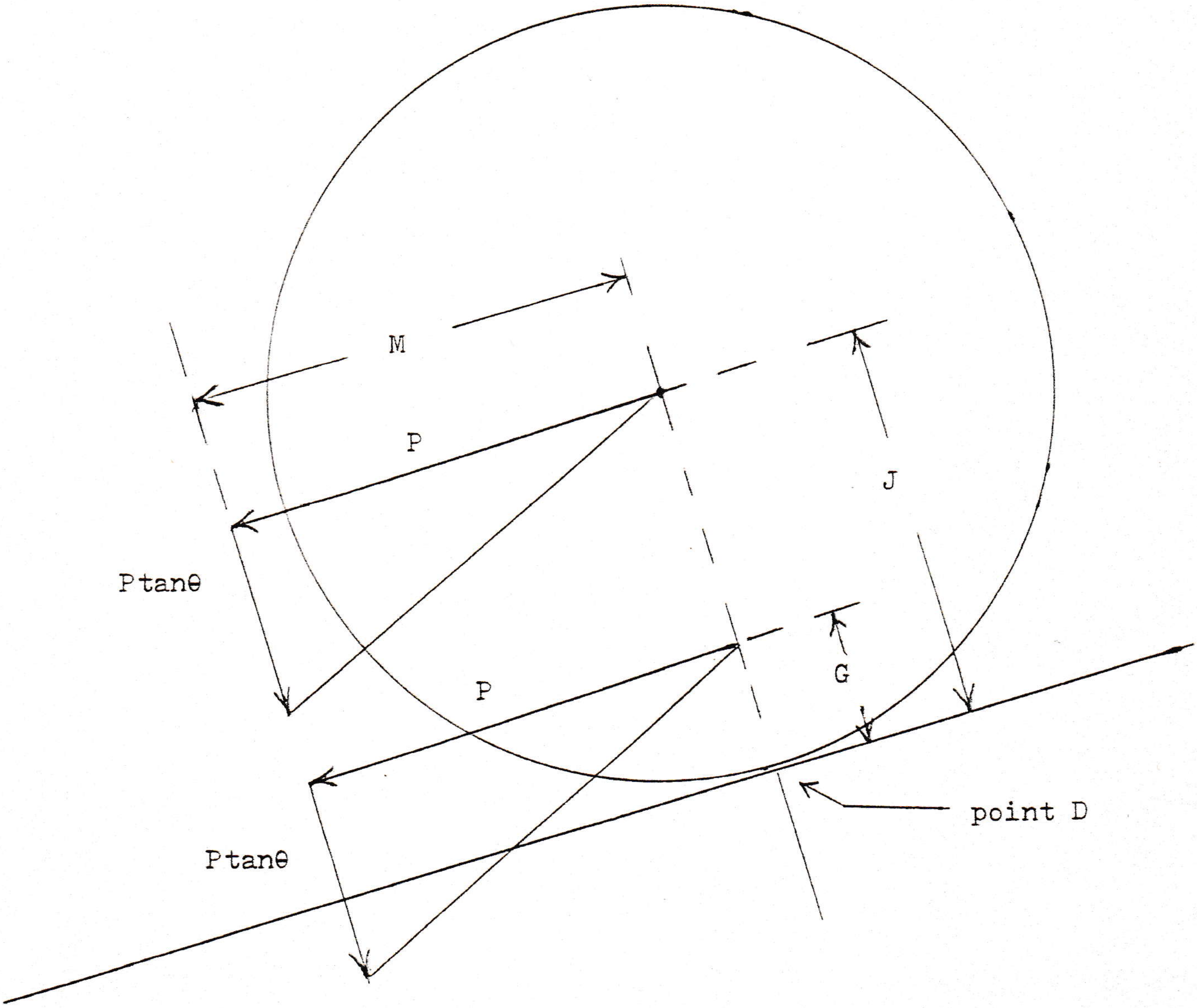


Figure 4. Free Body Diagram of Rear Wheel

The next variable that needed to be determined was FWS, or the front static weight. It was not possible to use the value given for FWS from the Nebraska Tractor Test because the front and rear weight changed when the tractor was operating on a slope. The following free body diagram was set up for the tractor in a static condition on a slope:

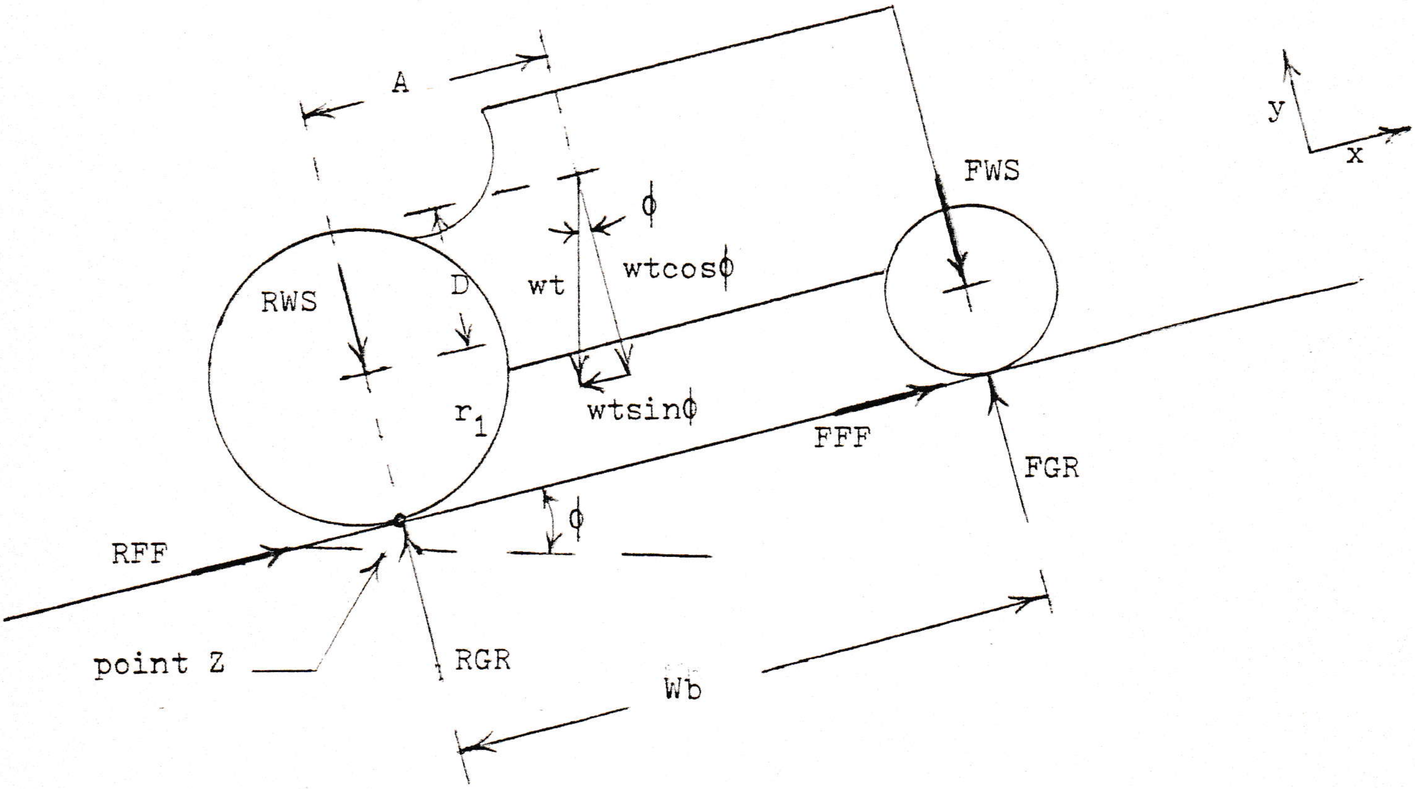


Figure 5. Free Body Diagram to Determine FWS and RWS

The variables that were used in the free body diagram were defined as follows:

RWS = rear weight static, the component of the weight of the tractor that acted through the center of the rear axle and was perpendicular to the soil's surface

RFF = the friction force of the soil that acted upon the rear tire in a direction parallel to the soil's surface

RGR = rear ground reaction, the reaction of the ground upon the rear tire that acted through the center of the rear axle in a direction perpendicular to the soil's surface

A = the distance measured parallel to the soil's surface from the center of the rear axle to the center of gravity of the tractor

D = the distance measured perpendicular to the soil's surface from the center of the rear axle to the center of gravity of the tractor

ϕ = the angle of inclination of the soil's surface with respect to the horizontal

wt = total weight of the tractor in the ballasted condition as measured from the Nebraska Tractor Test that acted at the center of gravity of the tractor

wtcosϕ = the component of the weight that acted perpendicular to the soil's surface

wtsinϕ = the component of the weight that acted parallel to the soil's surface

r_1 = the static loaded radius of the rear tire

Wb = the wheelbase of the tractor

FWS = front weight static, the component of the weight of the tractor that acted through the center of the front axle and was perpendicular to the soil's surface

FFF = the friction force of the soil that acted on the front tire in a direction parallel to the soil's surface

FGR = front ground reaction, the reaction of the ground upon the front tire that acted through the center of the front axle in a direction perpendicular to the soil's surface

The first step was to sum the moments around point Z such that the moment created by the total weight equalled the moment created only by the FWS:

$$\sum M_Z = - wt\cos\phi * A + wt\sin\phi * (D + r_1) = -FWS*Wb$$

Rearranging terms:

$$FWS = \frac{wt\cos\phi * A - wt\sin\phi * (D + r_1)}{Wb}$$

An expression for FWS had now been obtained and an expression for RWS was obtained by summing the forces in the y direction:

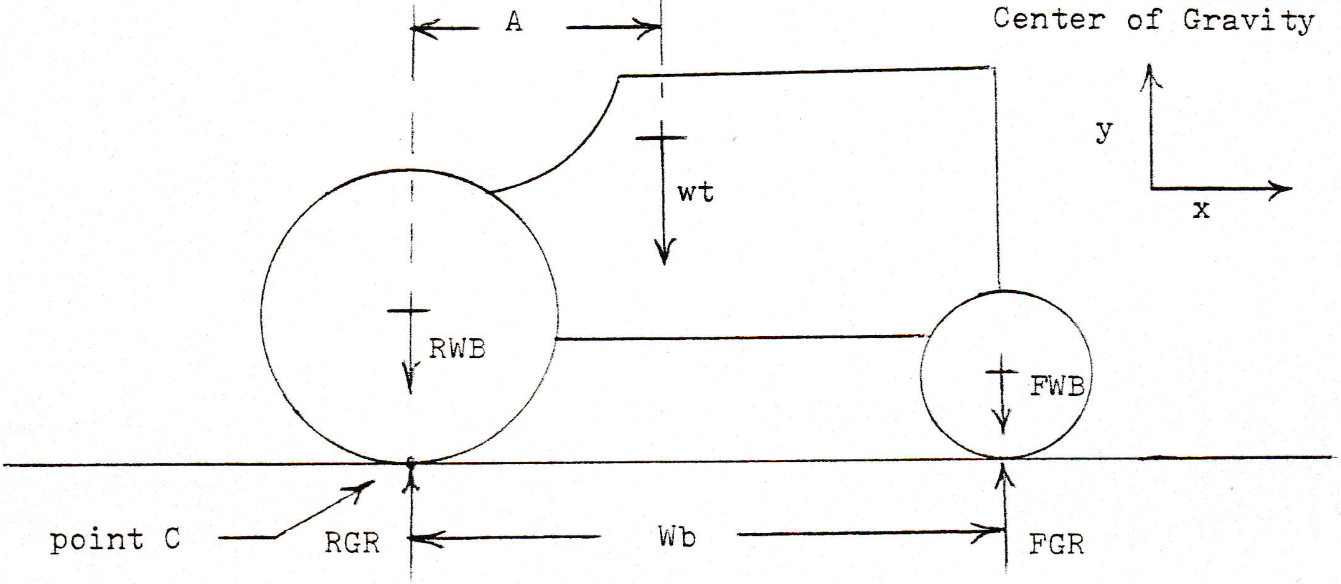
$$\sum F_y = RGR + FGR - wt\cos\phi = RGR + FGR - RWS - FWS$$

Rearranging terms:

$$RWS = wt\cos\phi - FWS$$

An expression had now been obtained for RWS and FWS in terms of the weight, the angle ϕ, the distance D, the distance A, the rear tire radius r_1, and the wheelbase Wb. The wheelbase and the ballasted weight were found from the Nebraska Tractor Test. The reason that it was decided to use the ballasted weight was that most tractors were operated with ballast and it was thought this represented actual field conditions more accurately than using the unballasted weight. The rear tire radius was also found by finding the appropriate loaded radius that was given for that particular tire size. The angle of inclination of the soil, ϕ, that the tractor was operating on was a specified condition so it was a known value. The only two variables that were not readily known were the distances A and D which located the position of the center of gravity of the tractor. The Nebraska Tractor Test only gave the location of the center of gravity for an unballasted tractor and not for the ballasted tractor. The following free body diagram was set up to help determine the ballasted center of gravity of the tractor in the static condition:

Figure 6. Free Body Diagram to Determine Ballasted Center of Gravity



The variables that were used in the free body diagram were defined as follows:

RWB = the rear weight with ballast

FWB = the front weight with ballast

wt = weight of the tractor with ballast

Wb = the wheelbase of the tractor

A = the horizontal distance from the center of the rear axle to the location of the ballasted center of gravity of the tractor

RGR = the rear ground reaction, the reaction of the soil on the rear tire in a vertical direction

FGR = the front ground reaction, the reaction of the soil on the front tire in a vertical direction

The first step was to note that the moment caused by the total weight must equal the moment caused by the FWB:

$$wt*A = FWB*Wb$$

Rearranging terms:

$$A = \frac{FWB*Wb}{wt}$$

This relation gave the horizontal location of the center of gravity in terms of the FWB, Wb, and wt. The weight, wt, for the ballasted tractor was found from the Nebraska Tractor Test. The Nebraska Tractor Test also gave the FWB and the Wb so it was possible to calculate the distance A. It was still necessary to find the vertical location of the ballasted center of gravity of the tractor. By definition, the center of gravity was that point where all of the mass of the body was considered to have been concentrated. Intuitively, the center of gravity was thought of as the point where a thin wire was passed through and the tractor was held by the wire at that point and no matter how the tractor was rotated, it always remained in equilibrium. In order to determine the vertical position of the center of gravity, the tractor was considered to be held by a thin wire through the center of gravity in the position shown in the following free body diagram:

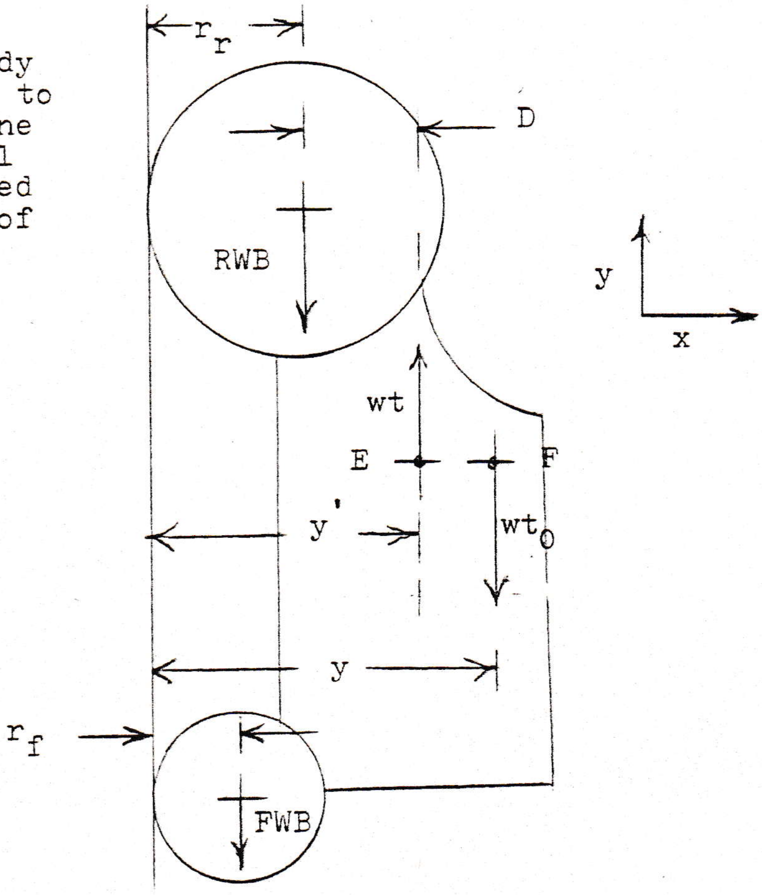


Figure 7. Free Body Diagram to Determine Vertical Ballasted Center of Gravity

The variables that were used in the free body diagram were defined as follows:

r_r = the loaded rear tire radius

D = the horizontal distance between the center of the rear axle and the ballasted center of gravity

wt = the ballasted weight of the tractor(the force on a wire that held the tractor through the ballasted center of gravity)

RWB = rear weight ballast, the ballasted weight added to the rear of the tractor

E = the point of the location of the ballasted center of gravity

F = the point of the location of the unballasted center of gravity

wt_o = the unballasted weight of the tractor

y' = the horizontal distance from the left side of the tires to the ballasted center of gravity

y = the horizontal distance from the left side of the tires to the unballasted center of gravity

FWB = front weight ballast, the ballasted weight added to the front of the tractor

r_f = the loaded front tire radius

The first step in analyzing this free body diagram was to sum the moments around point E:

$$\sum M_E = 0 = RWB(y' - r_r) + FWB(y' - r_f) - wt_o(y - y')$$

Rearranging terms:

$$y*wt_o - y'*wt_o = RWB*y' - RWB*r_r + FWB*y' - FWB*r_f$$

$$y*wt_o + RWB*r_r + FWB*r_f = y'\ (wt_o + RWB + FWB)$$

$$y' = \frac{y*wt_o + RWB*r_r + FWB*r_f}{wt_o + RWB + FWB}$$

$$D = y' - r_r$$

$$D = \frac{y*wt_o + RWB*r_r + FWB*r_f}{\cancel{wt_o + RWB + FWB}} - r_r$$

In making this free body diagram the assumption was made that all of the ballast that was added was put on in the form of cast iron wheel weights or liquid in the tires. This assumption allowed these added masses to be thought of as being concentrated at the center of the axles. All of the variables in the above expression for D were found from the Nebraska Tractor Tests except for the radius of the tires which required a table that gave the appropriate radius for the tire size given in the Nebraska Tractor Test. Sometimes ballast was added in the Nebraska Tractor Tests in the form of "suitcase weights", or cast iron weights placed at the front of the tractor. If this was the case, it became necessary to look at the following free body diagram:

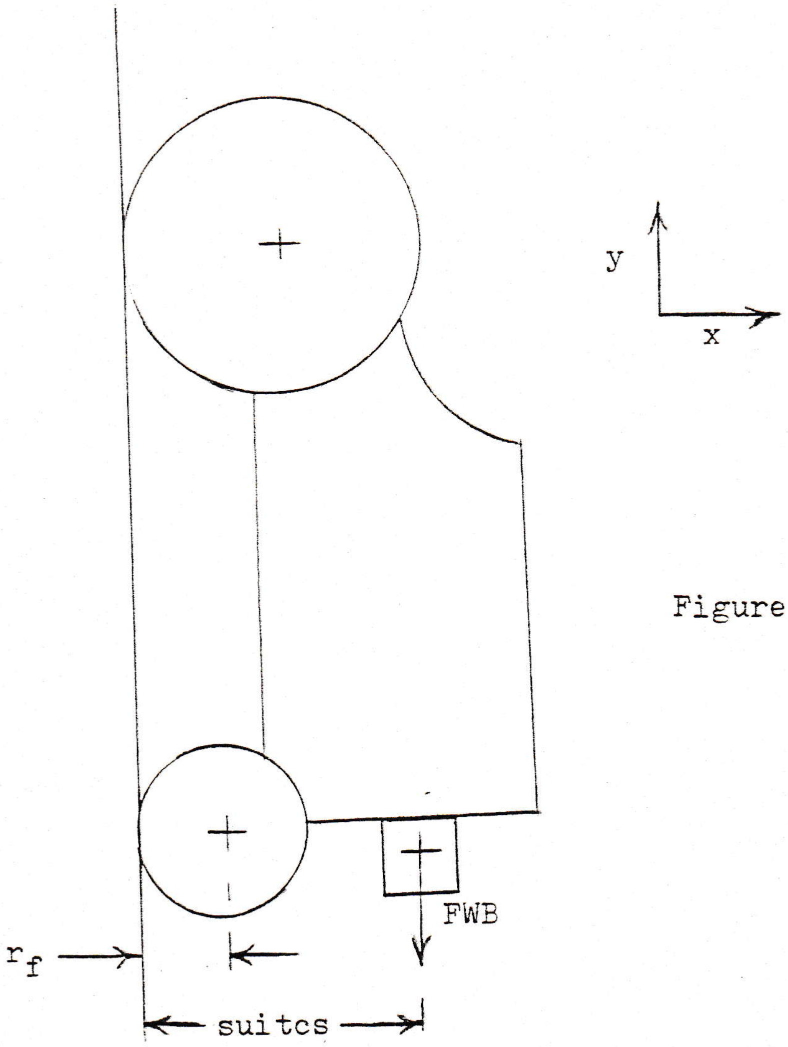


Figure 8. Free Body Diagram of Suitcase Weights

The variables that were used in the free body diagram were defined as follows:

FWB = front weight ballast, the ballast weight added to the front of the tractor

r_f = the loaded front tire radius

suitcs = the horizontal distance from the center of the rear axle to the location of the center of gravity of the suitcase weights

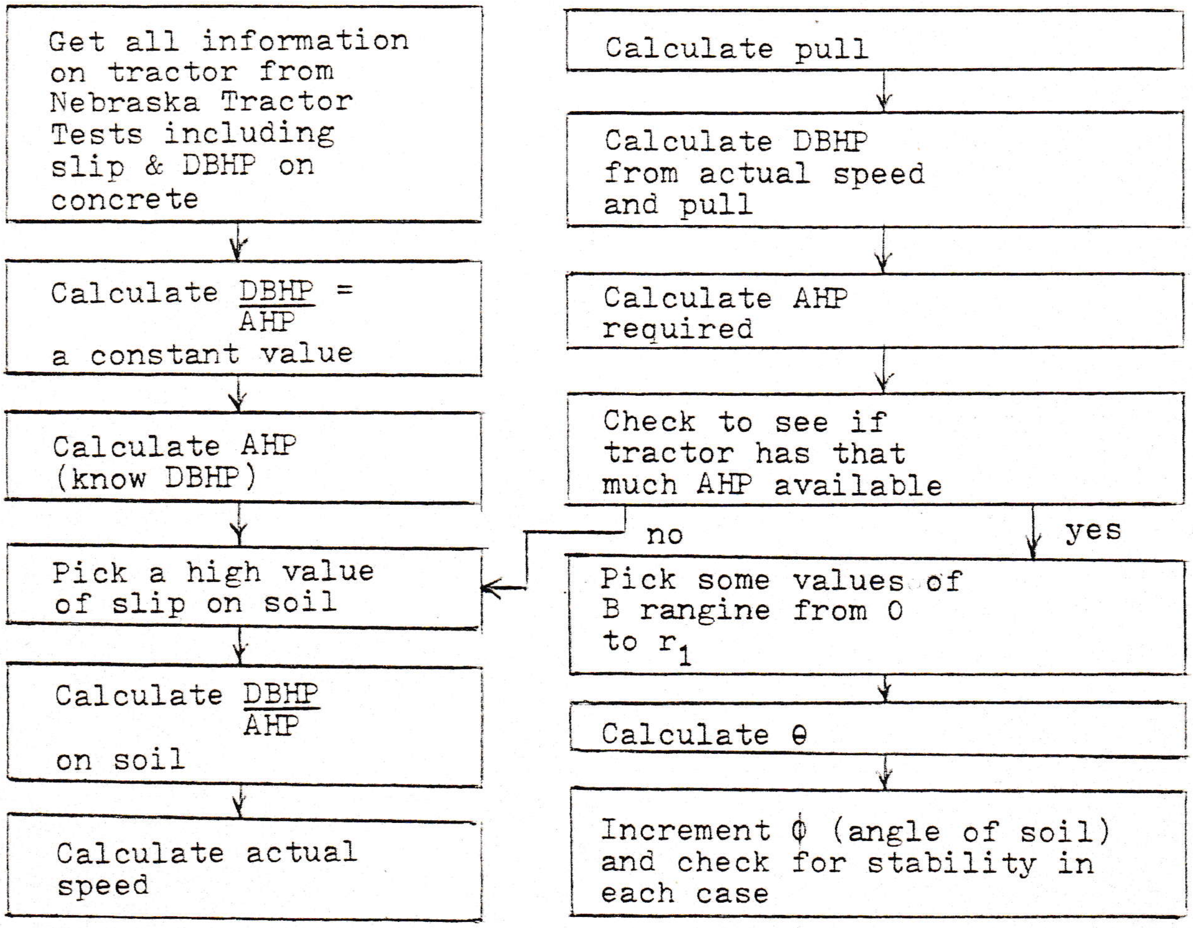
If there was a note in the Nebraska Tractor Test that the front ballast was added in the suitcase form, it became necessary to change the distance r_f to r_f + suitcs as was evident from an examination of the free body diagram above for the moment arm of FWB. In order to take this suitcase weight option into account, the term r_f was replaced by the quantity r_f + suitcs as shown below:

$$D = \frac{y*wt_o + RWB*r_r + FWB(r_f + \text{suitcs})}{wt_o + RWB + FWB} - r_r$$

This equation for D allowed for the case where there were no suitcase weights and therefore suitcs was set equal to zero, and also allowed for the case where there was suitcase weights and this distance was used as a value for suitcs. To get a good value for suitcase if there was suitcase weights, it would have been necessary to go to the tractor and measure the vertical distance from the center of the front axle to the center of gravity of the suitcase weights.

The only variable left that had not been determined was P, the horizontal component of the drawbar pull. One of the first questions that arose was how much more can a tractor pull when operating on a slope compared to operating on level ground due to the weight of the tractor shifting to the rear which allowed the tractor to pull more. Since there was not much material available on work done in this area, it was assumed that the maximum amount of pull the tractor could develop on a slope was exactly equal to the greatest amount of pull it could develop on level ground. It was also not known if engine power, traction, or stability governed the maximum amount of pull so the decision was made to use the Nebraska Tractor Test and Frank Zoz's traction chart to analyze the situation. The best way to describe how these tools were implemented was to examine the following flow chart which was the end result of the analysis:

Figure 9.


Get all information on tractor from Nebraska Tractor Tests including slip & DBHP on concrete
Calculate DBHP/AHP = a constant value
Calculate AHP (know DBHP)
Pick a high value of slip on soil
Calculate DBHP/AHP on soil
Calculate actual speed
Calculate pull
Calculate DBHP from actual speed and pull
Calculate AHP required
Check to see if tractor has that much AHP available
no
yes
Pick some values of B rangine from 0 to r1
Calculate θ
Increment ϕ (angle of soil) and check for stability in each case

The first step in the flow chart was to get all of the measurements of distances and weights necessary for the rest of the calculations in the flow chart. The next step was to get the slip and the horsepower developed on concrete for any gear of interest from the "Maximum Power in Selected Gears" section of the Nebraska Tractor Test. The next step was to calculate the tractive efficiency, DBHP/AHP, of the tractor on concrete. Since Hunt had developed the equations for relating slip and tractive efficiency for Zoz's traction chart, it then became possible to calculate the tractive efficiency knowing the slip recorded on concrete by the following equations:

TE = (-(AA*slip+CC)+SQRT((AA*Slip+CC)**2-4*(BB*Slip*Slip+DD*Slip+EE)))/2

TE = tractive efficiency, decimal

Slip = drive wheel slip, decimal, slip on concrete from the Nebraska Tractor Test

AA = 5.124

BB = 6.556

CC = -1.596

DD = -5.376

EE = .6450

Since the value of the tractive efficiency was now known and the value of the drawbar horsepower was known from the Nebraska Tractor Test, the decision was made to use the following equations to determine the maximum axle horsepower available to the wheels:

$$TE = \frac{DBHP}{AHP}$$

$$AHP = \frac{DBHP}{TE}$$

AHP = axle horsepower

DBHP = drawbar horsepower

TE = tractive efficiency on concrete, decimal

It was now possible to calculate the AHP, the axle horsepower, which was the maximum amount of power available to drive the rear wheels. The main objective was to determine how much pull the tractor would develop on a given soil with a given hitch. The decision was made to use the approach of picking a high value of slip on the chosen soil type and hitch type and then calculating the axle horsepower needed to run a given tractor with this slip. If the axle horsepower required was more than the amount we had available, it was decided to try a lower value of slip and claculate a new required axle horsepower. This process of lowering the slip was repeated until the point was reached where the axle horsepower required to operate at that slip was equal to or less than the amount of axle horsepower that was available.

The next step in the flow chart was to pick a high starting value of slip for a given tractor operating on a given soil with a given hitch type. Since Zoz's traction chart only went up to slips of 30%, the decision was made to use 30% slip as the starting point. The soil types that were used were the same ones that Zoz used on his traction chart and they were firm, tilled, and sandy. The hitch types that were used were also the same ones Zoz used on his chart and they were integral, seim-integral, and towed.

Since a value of slip had now been obtained, it was possible to use Hunt's equations of Zoz's traction chart to calculate the tractive efficiency using the equations below which had different coefficients depending on the chosen soil type and hitch type:

$$TE = \frac{-(A*S + C) + \sqrt{(A*S + C)^2 - 4(B*S^2 + D*S + E)}}{2}$$

TE = the tractive efficiency, decimal

S = drive wheel slip, decimal

	A	B	C	D	E
concrete	5.124	6.556	-1.596	-5.376	.6450
firm soil	6.928	12.00	-1.129	-7.749	.3895
tilled soil	6.928	12.00	-.7369	-7.355	.2375
sand	8.000	16.00	-.2280	-8.772	.1812

It was now possible to calculate the actual travel speed of the tractor on the soil it was operating on by the following equations:

$$\text{Slip} = \frac{\text{noload} - \text{aloads}}{\text{noload}}$$

Rearranging terms:

$$\text{Slip} = 1 - \frac{\text{aloads}}{\text{noload}}$$

$$1 - \text{Slip} = \frac{\text{aloads}}{\text{noload}}$$

$$\text{aloads} = \text{noload}*(1 - \text{Slip})$$

aloads = actual load speed, speed of the tractor with a load operating on the given soil, mph

noload = no load speed, advertised speed of the tractor in the gear chosen from the Nebraska Tractor Test, mph

Slip = drive wheel slip, it was the value that was picked, decimal

The next block in the flow chart was the calculation of the drawbar pull. Since the slip was known, it became possible to calculate the pull by using Hunt's equations of Zoz's traction chart that related slip to the quantity drawbar pull divided by rear tractor weight:

$$\text{Slip} = A - \sqrt{A^2 - \frac{\text{DBPull}}{B*\text{SRAW}}}$$

Slip = drive wheel slip, decimal

DBPull = drawbar pull(same units as SRAW)

SRAW = static rear axle weight of tractor(same units as DBPull)

	concrete			firm	
	A	B		A	B
R = .25	.165	37.85	int.	.388	7.77
R = .20	.166	35.81	semi-	.333	8.23
R = .25	.166	34.12	towed	.300	8.45

	tilled		sand	
	A	B	A	B
int.	.348	6.31	.303	4.12
semi-	.321	6.40	.313	3.62
towed	.322	5.69	.297	3.71

R = ratio of the drawbar height to the wheelbase in a concrete operating comdition

Since the value of the drawbar pull and the speed was known, it was then possible to calculate the drawbar horsepower developed by the tractor in soil:

DBHP = (DBPull*aloads*5280)/(3600*550)

DBPull = the drawbar pull calculated earlier, pounds

aloads = actual load speed calculated earlier, mph

DBHP = drawbar horsepower developed by the tractor on soil

The last step was to calculate the axle horsepower required. Since the tractive efficiency and the drawbar horsepower were known, it was possible to calculate the required axle horsepower by the following equations:

$$TE = \frac{DBHP}{RQDAHP}$$

Rearranging terms:

$$RQDAHP = \frac{DBHP}{TE}$$

DBHP = drawbar horsepower calculated earlier, horsepower

TE = tractive efficiency on soil calculated earlier, decimal

RQDAHP = required axle horsepower, horsepower

It now became possible to check if the tractor had enough axle horsepower available to meet the required axle horsepower that was just calculated. If it did not, the next step was to go back and pick a lower value of slip and go through the whole process again. If it did have enough axle horsepower, the maximum pull the tractor would generate for the conditions chosen became the previously calculated value.

After going through all of the derivations above, it then became possible to calculate FWD and determine the stability of the tractor. The best approach to making all of these calculations was to develop a simple computer program that performed these calculations very fast and allowed for the many different operating conditions that were of interest to the user of the program.

Development of the Fortran Computer Program

The best method of performing all of the calculations that were involved in predicting tractor stability was to write a Fortran computer program. The main goal in writing this program was to make it as simple as possible and to set up the program in such a manner that all the input information the user needed to use in the program was available from one sheet of paper that contained the Nebraska Tractor Test results for the tractor model in question. The program was written in Fortran and was run on an IBM 360 computer at the University of Illinois. The best method of explaining this program was to present the whole program and then go through and break down the program step by step and explain the function of each statement in the program.

```
           $JOB
  1                 REAL NOLOAD
  2                 READ,GEAR,CSLIP,DBHP,ORGLWT,BLSTWT,CGRAVY,SOIL,NOLOAD,
               XHITCH,WB,SRAW,SFAW,RTIRE,FTIRE,STCASE,RWB,FWB
  3                 PRINT80
  4             80  FORMAT(' ',3X,'GEAR',6X,'CSLIP',5X,'DBHP',5X,'ORGLWT',
               X4X,'BLSTWT',4X,'CGRAVY')
  5                 PRINT81,GEAR,CSLIP,DBHP,ORGLWT,BLSTWT,CGRAVY
  6             81  FORMAT('0',4X,F3.0,5X,F5.2,5X,F6.2,4X,F6.0,4X,F6.0,4X,
               XF6.2)
  7                 PRINT82
  8             82  FORMAT('-',3X,'SOIL',5X,'NOLOAD',4X,'HITCH',7X,'WB',
               X7X,'SRAW',6X,'SFAW')
  9                 PRINT83,SOIL,NOLDAD,HITCH,WB,SRAW,SFAW
 10             83  FORMAT('0',4X,F3.0,5X,F5.2,7X,F3.0,5X,F6.2,4X,F6.0,
               X4X,F6.0)
 11                 PRINT84
 12             84  FORMAT('-',2X,'RTIRE',5X,'FTIRE',5X,'STCASE',5X,
               X'RWB',7X,'FWB')
 13                 PRINT85,RTIRE,FTIRE,STCASE,RWB,FWB
 14             85  FORMAT('0',1X,F7.0,3X,F7.0,3X,F7.2,4X,F6.0,4X,F6.0)
 15                 IF(RTIRE.EQ.9516)RRADII=15.2
 16                 IF(RTIRE.EQ.184161)RRADII=19.5
 17                 IF(RTIRE.EQ.8324)RRADII=18.2
 18                 IF(RTIRE.EQ.9524)RRADII=19.0
 19                 IF(RTIRE.EQ.11224)RRADII=19.0
 20                 IF(RTIRE.EQ.12424)RRADII=20.8
 21                 IF(RTIRE.EQ.13624)RRADII=21.5
 22                 IF(RTIRE.EQ.14924)RRADII=22.4
```

```
      IF(RTIRE.EQ.16924)RRADII=23.1
      IF(RTIRE.EQ.13626)RRADII=22.6
      IF(RTIRE.EQ.14926)RRADII=23.4
      IF(RTIRE.EQ.16926)RRADII=24.1
      IF(RTIRE.EQ.18426)RRADII=25.6
      IF(RTIRE.EQ.23126)RRADII=27.7
      IF(RTIRE.EQ.28126)RRADII=27.9
      IF(RTIRE.EQ.11228)RRADII=21.9
      IF(RTIRE.EQ.12428)RRADII=22.8
      IF(RTIRE.EQ.13628)RRADII=23.5
      IF(RTIRE.EQ.14928)RRADII=24.4
      IF(RTIRE.EQ.16928)RRADII=25.1
      IF(RTIRE.EQ.18428)RRADII=26.7
      IF(RTIRE.EQ.14930)RRADII=25.5
      IF(RTIRE.EQ.16930)RRADII=26.1
      IF(RTIRE.EQ.18430)RRADII=27.4
      IF(RTIRE.EQ.23130)RRADII=29.9
      IF(RTIRE.EQ.24532)RRADII=31.5
      IF(RTIRE.EQ.16934)RRADII=28.1
      IF(RTIRE.EQ.18434)RRADII=29.4
      IF(RTIRE.EQ.23134)RRADII=32.0
      IF(RTIRE.EQ.13936)RRADII=26.9
      IF(RTIRE.EQ.11238)RRADII=26.9
      IF(RTIRE.EQ.13638)RRADII=28.6
      IF(RTIRE.EQ.15538)RRADII=28.6
      IF(RTIRE.EQ.16938)RRADII=30.4
      IF(RTIRE.EQ.18438)RRADII=31.6
      IF(RTIRE.EQ.20838)RRADII=32.8
      IF(FTIRE.EQ.40012)FRADII=10.0
      IF(FTIRE.EQ.60014)FRADII=12.5
      IF(FTIRE.EQ.50015)FRADII=12.0

      IF(FTIRE.EQ.7515)FRADII=13.6
      IF(FTIRE.EQ.9515)FRADII=13.9
      IF(FTIRE.EQ.1115)FRADII=14.4
      IF(FTIRE.EQ.55016)FRADII=13.1
      IF(FTIRE.EQ.60016)FRADII=13.5
      IF(FTIRE.EQ.65016)FRADII=13.9
      IF(FTIRE.EQ.75016)FRADII=14.7
      IF(FTIRE.EQ.100016)FRADII=16.0
      IF(FTIRE.EQ.110016)FRADII=17.3
      IF(FTIRE.EQ.14161)FRADII=17.3
      IF(FTIRE.EQ.75018)FRADII=15.9
      IF(FTIRE.EQ.75020)FRADII=16.9
      IF(FTIRE.EQ.95020)FRADII=17.9
      PRINT86
   86 FORMAT('-',2X,'RRADII',4X,'FRADII')
      PRINT87,RRADII,FRADII
   87 FORMAT('0',2X,F6.2,4X,F6.2)
C    NOW NEED TO CALCULATE CENTER OF GRAVITY WITH BALLAST
      BCTGRX=SFAW*WB/BLSTWT
      BCTGRY=(CGRAVY*ORGLWT+RWB*RRADII+FWB*(FRADII+STCASE))/
     X(ORGLWT+RWB+FWB)
      PRINT88
   88 FORMAT('-',2X,'BCTGRX',4X,'BCTGRY')
      PRINT89,BCTGRX,BCTGRY
   89 FORMAT('0',2X,F6.2,4X,F6.2)
C    NOW WANT TO CALCULATE TRACTIVE EFFICIENCY
C   TRACTIVE EFFICIENCY=DRAWBAR HORSEPOWER/AXLE HORSEPOWER
      AA=5.124
      BB=6.556
      CC=-1.596
      DD=-5.376
      EE=.6450
      SLIP=CSLIP
      TE=(-(AA*SLIP+CC)+SQRT((AA*SLIP+CC)**2-4*(BB*
     XSLIP*SLIP+DD*SLIP+EE)))/2
```

```
      PRINT90
   90 FORMAT('-',2X,'TRACTIVE EFFICIENCY ON CONCRETE')
      PRINT91,TE
   91 FORMAT('0',13X,F5.2)
      AHP=DBHP/TE
      PRINT92
   92 FORMAT('-',2X,'AXLE HORSEPOWER')
      PRINT93,AHP
   93 FORMAT('0',6X,F6.2)
      SLIP=.30
      GO TO 10
   11 SLIP=SLIP-.01
   10 CONTINUE
      IF(SOIL.EQ.3)GO TO 12
      IF(SOIL.EQ.4)GO TO 13
      AA=6.928
      BB=12.0
      CC=-1.129
      DD=-7.749
      EE=.3895
      TE=(-(AA*SLIP+CC)+SQRT((AA*SLIP+CC)**2-4*(BB*
     XSLIP*SLIP+DD*SLIP+EE)))/2
      ALOADS=NOLOAD*(1-SLIP)
      GO TO 14
   12 CONTINUE

      AA=6.928
      BB=12.0
      CC=-.7369
      DD=-7.355
      EE=.2375
      TE=(-(AA*SLIP+CC)+SQRT((AA*SLIP+CC)**2-4*(BB*
     XSLIP*SLIP+DD*SLIP+EE)))/2
      ALOADS=NOLOAD*(1-SLIP)
      GO TO 15
   13 CONTINUE
      AA=8.
      BB=16.
      CC=-.228
      DD=-8.772
      EE=.1812
      TE=(-(AA*SLIP+CC)+SQRT((AA*SLIP+CC)**2-4*(BB*
     XSLIP*SLIP+DD*SLIP+EE)))/2
      ALOADS=NOLOAD*(1-SLIP)
   14 CONTINUE
   15 CONTINUE
      IF(SOIL.EQ.2.AND.HITCH.EQ.1)GO TO 16
      IF(SOIL.EQ.2.AND.HITCH.EQ.2)GO TO 17
      IF(SOIL.EQ.2.AND.HITCH.EQ.3)GO TO 18
      IF(SOIL.EQ.3.AND.HITCH.EQ.1)GO TO 19
      IF(SOIL.EQ.3.AND.HITCH.EQ.2)GO TO 20
      IF(SOIL.EQ.3.AND.HITCH.EQ.3)GO TO 21
      IF(SOIL.EQ.4.AND.HITCH.EQ.1)GO TO 22
      IF(SOIL.EQ.4.AND.HITCH.EQ.2)GO TO 23
      IF(SOIL.EQ.4.AND.HITCH.EQ.3)GO TO 24
   16 CONTINUE
      AAA=.388
      BBB=7.77
      GO TO 25
   17 CONTINUE
      AAA=.333
      BBB=8.23
      GO TO 25
   18 CONTINUE
      AAA=.300
      BBB=8.45
      GO TO 25
   19 CONTINUE
      AAA=.348
      BBB=6.31
      GO TO 25
   20 CONTINUE
      AAA=.321
      BBB=6.40
      GO TO 25
   21 CONTINUE
      AAA=.322
      BBB=5.69
      GO TO 25
   22 CONTINUE
      AAA=.303
      BBB=4.12
      GO TO 25
   23 CONTINUE
      AAA=.313
      BBB=3.62

      GO TO 25
   24 CONTINUE
      AAA=.297
      BBB=3.71
   25 CONTINUE
      DBPULL=BBB*SRAW*(AAA*AAA-(AAA-SLIP)**2)
      DBHP=(DBPULL*ALOADS*5280)/(3600*550)
      RQDAHP=DBHP/TE
      IF(RQDAHP.GT.AHP)GO TO 11
      PRINT94
   94 FORMAT('-',2X,'DBPULL',5X,'DBHP',5X,'RQDAHP',5X,'SLIP',
     X5X,'ALOADS',6X,'TE ON SOIL')
      PRINT95,DBPULL,DBHP,RQDAHP,SLIP,ALOADS,TE
   95 FORMAT('0',1X,F7.0,3X,F7.2,3X,F7.2,5X,F4.2,5X,F6.2,6X,F5.2)
      IF(HITCH.EQ.1)DWC=.65
      IF(HITCH.EQ.2)DWC=.45
      IF(HITCH.EQ.3)DWC=.25
      PRINT96
   96 FORMAT('-',3X,'DWC')
      PRINT97,DWC
   97 FORMAT('-',2X,F4.2)
      H=0
      DO 26 I=1,11
      THETA=ATAN(DWC-H/WB)
      THETAS=THETA*180/3.1415
      PRINT58
   58 FORMAT('-',2X,'     ')
      PRINT59
   59 FORMAT('-',2X,'       ')
      PRINT98
   98 FORMAT('1',4X,'H',7X,'THETAS')
      PRINT99,H,THETAS
   99 FORMAT('0',2X,F7.2,4X,F5.2)
      PHI=0
      DO 27 J=1,45
      FWS=(BLSTWT*COS(PHI)*BCTGRX-BLSTWT*SIN(PHI)*BCTGRY)/WB
      FWD=DBPULL*TAN(THETA)+FWS-DBPULL*DWC
      PHIS=PHI*180/3.1415
      PRINT70
   70 FORMAT('-',3X,'FWS',7X,'FWD',7X,'PHIS')
      PRINT71,FWS,FWD,PHIS
   71 FORMAT('0',2X,F7.0,3X,F7.0,3X,F5.0)
      PHI=PHI+3.1415*2/180
      IF(FWD.LT.0)GO TO 50
   27 CONTINUE
   50 CONTINUE
      H=H+RRADII/10.
   26 CONTINUE
      STOP
      END
```

```
         SENTRY
 GEAR       CSLIP       DBHP      ORGLWT     BLSTWT     CGRAVY
  5.        0.15       55.92      7440.      10760.      39.90

 SOIL      NOLOAD      HITCH        WB        SRAW       SFAW
  2.        2.50         1.       87.50       8170.      2590.

RTIRE      FTIRE      STCASE       RWB        FWB
18434.     75018.      0.00       3160.       160.

RRADII     FRADII
 29.40      15.90

BCTGRX     BCTGRY
 21.06      36.46

TRACTIVE EFFICIENCY ON CONCRETE
                0.85

AXLE HORSEPOWER
      66.13

DBPULL      DBHP      RQDAHP      SLIP      ALOADS      TE ON SOIL
 8348.      41.74      65.10      0.25       1.88         0.64

 DWC

0.65
```

```
  H          THETAS
   0.00      33.02

FWS          FWD           PHIS
  2590.       2590.          0.

FWS          FWD           PHIS
  2432.       2432.          2.

FWS          FWD           PHIS
  2271.       2271.          4.

FWS          FWD           PHIS
  2107.       2107.          6.

FWS          FWD           PHIS
  1941.       1941.          8.

FWS          FWD           PHIS
  1772.       1772.         10.

FWS          FWD           PHIS
  1601.       1601.         12.

FWS          FWD           PHIS
  1428.       1428.         14.

FWS          FWD           PHIS
  1254.       1254.         16.

FWS          FWD           PHIS
  1078.       1078.         18.

FWS          FWD           PHIS
   900.        900.         20.

FWS          FWD           PHIS
   722.        722.         22.

FWS          FWD           PHIS
   543.        543.         24.

FWS          FWD           PHIS
   363.        363.         26.

FWS          FWD           PHIS
   182.        182.         28.
```

```
 FWS          FWD          PHIS
        1.           1.     30.

 FWS          FWD          PHIS
   -179.        -179.       32.



   H        THETAS
    2.94     31.65

 FWS          FWD          PHIS
  2590.        2310.         0.

 FWS          FWD          PHIS
  2432.        2151.         2.

 FWS          FWD          PHIS
  2271.        1990.         4.

 FWS          FWD          PHIS
  2107.        1827.         6.

 FWS          FWD          PHIS
  1941.        1660.         8.

 FWS          FWD          PHIS
  1772.        1492.        10.

 FWS          FWD          PHIS
  1601.        1321.        12.

 FWS          FWD          PHIS
  1428.        1148.        14.

 FWS          FWD          PHIS
  1254.         973.        16.

 FWS          FWD          PHIS
  1078.         797.        18.
```

```
FWS         FWD         PHIS
  900.        620.        20.

FWS         FWD         PHIS
  722.        441.        22.

FWS         FWD         PHIS
  543.        262.        24.

FWS         FWD         PHIS
  363.         82.        26.

FWS         FWD         PHIS
  182.        -98.        28.



   H         THETAS
  5.88       30.23

FWS         FWD         PHIS
 2590.       2029.         0.

FWS         FWD         PHIS
 2432.       1871.         2.

FWS         FWD         PHIS
 2271.       1710.         4.

FWS         FWD         PHIS
 2107.       1546.         6.

FWS         FWD         PHIS
 1941.       1380.         8.

FWS         FWD         PHIS
 1772.       1211.        10.

FWS         FWD         PHIS
 1601.       1040.        12.

FWS         FWD         PHIS
 1428.        867.        14.
```

```
FWS          FWD          PHIS
 1254.         693.         16.

FWS          FWD          PHIS
 1078.         517.         18.

FWS          FWD          PHIS
  900.         339.         20.

FWS          FWD          PHIS
  722.         161.         22.

FWS          FWD          PHIS
  543.         -18.         24.




    H        THETAS
  8.82       28.78

FWS          FWD          PHIS
 2590.        1749.          0.

FWS          FWD          PHIS
 2432.        1591.          2.

FWS          FWD          PHIS
 2271.        1429.          4.

FWS          FWD          PHIS
 2107.        1266.          6.

FWS          FWD          PHIS
 1941.        1099.          8.

FWS          FWD          PHIS
 1772.         931.         10.

FWS          FWD          PHIS
 1601.         760.         12.

FWS          FWD          PHIS
 1428.         587.         14.
```

```
  FWS          FWD          PHIS
   1254.         412.         16.

  FWS          FWD          PHIS
   1078.         236.         18.

  FWS          FWD          PHIS
    900.          59.         20.

  FWS          FWD          PHIS
    722.        -120.         22.



   H         THETAS
  11.76      27.28

  FWS          FWD          PHIS
   2590.        1468.          0.

  FWS          FWD          PHIS
   2432.        1310.          2.

  FWS          FWD          PHIS
   2271.        1149.          4.

  FWS          FWD          PHIS
   2107.         985.          6.

  FWS          FWD          PHIS
   1941.         819.          8.

  FWS          FWD          PHIS
   1772.         650.         10.

  FWS          FWD          PHIS
   1601.         479.         12.

  FWS          FWD          PHIS
   1428.         307.         14.

  FWS          FWD          PHIS
   1254.         132.         16.

  FWS          FWD          PHIS
   1078.         -44.         18.
```

```
 H          THETAS
 14.70      25.73

FWS        FWD        PHIS
 2590.      1188.        0.

FWS        FWD        PHIS
 2432.      1030.        2.

FWS        FWD        PHIS
 2271.       869.        4.

FWS        FWD        PHIS
 2107.       705.        6.

FWS        FWD        PHIS
 1941.       538.        8.

FWS        FWD        PHIS
 1772.       370.       10.

FWS        FWD        PHIS
 1601.       199.       12.

FWS        FWD        PHIS
 1428.        26.       14.

FWS        FWD        PHIS
 1254.      -149.       16.


 H          THETAS
 17.64      24.15

FWS        FWD        PHIS
 2590.       907.        0.

FWS        FWD        PHIS
 2432.       749.        2.

FWS        FWD        PHIS
```

```
  2271.        588.        4.

 FWS          FWD         PHIS
  2107.        424.        6.

 FWS          FWD         PHIS
  1941.        258.        8.

 FWS          FWD         PHIS
  1772.         89.       10.

 FWS          FWD         PHIS
  1601.        -82.       12.



   H         THETAS
  20.58      22.53

 FWS          FWD         PHIS
  2590.        627.        0.

 FWS          FWD         PHIS
  2432.        469.        2.

 FWS          FWD         PHIS
  2271.        308.        4.

 FWS          FWD         PHIS
  2107.        144.        6.

 FWS          FWD         PHIS
  1941.        -23.        8.



   H         THETAS
  23.52      20.87

 FWS          FWD         PHIS
  2590.        346.        0.

 FWS          FWD         PHIS
  2432.        188.        2.

 FWS          FWD         PHIS
  2271.         27.        4.
 FWS          FWD           PHIS
  2107.        -137.          6.


  H          THETAS
  26.46       19.17

 FWS          FWD           PHIS
  2590.          66.          0.

 FWS          FWD           PHIS
  2432.         -92.          2.


  H          THETAS
  29.40       17.43

 FWS          FWD           PHIS
  2590.        -215.          0.
```

It was also necessary to use the following Nebraska Tractor Test to aid in the explanation of the computer program:

NEBRASKA TRACTOR TEST 1225—FORD 7600 DIESEL 16-SPEED

POWER TAKE-OFF PERFORMANCE

	Hp	Crank-shaft speed rpm	Fuel Consumption			Temperature Degrees F			Barometer inches of Mercury
			Gal per hr	Lb per hp-hr	Hp-hr per gal	Cooling medium	Air wet bulb	Air dry bulb	
MAXIMUM POWER AND FUEL CONSUMPTION									
Rated Engine Speed—Two Hours (PTO Speed—1020 rpm)									
	84.79	2100	5.399	0.446	15.70	199	60	75	28.890
Standard Power Take-off Speed (1000 rpm)—One Hour									
	85.16	2059	5.338	0.439	15.95	200	62	75	28.870
VARYING POWER AND FUEL CONSUMPTION—Two Hours									
	75.68	2204	5.118	0.473	14.79	196	62	75	.....
	0.00	2334	1.659	.....	.....	176	61	75	.....
	39.18	2282	3.463	0.619	11.31	178	58	76	.....
	86.38	2100	5.521	0.447	15.65	204	60	76	.....
	19.82	2310	2.542	0.897	7.80	174	60	75	.....
	57.93	2249	4.286	0.518	13.52	182	60	75	.....
Av	46.50	2246	3.765	0.567	12.35	185	60	75	28.840

DRAWBAR PERFORMANCE

Hp	Draw-bar pull lbs	Speed miles per hr	Crank-shaft speed rpm	Slip of drivers %	Fuel Consumption			Temp Degrees F			Barome-ter inches of Mercury
					Gal per hr	Lb per hp-hr	Hp-hr per gal	Cool-ing med	Air wet bulb	Air dry bulb	
Maximum Available Power—Two Hours 8th (5PD) Gear											
65.33	5625	4.36	2100	10.98	5.251	0.563	12.44	176	54	62	28.810
75% of Pull at Maximum Power—Ten Hours 8th (5PD) Gear											
54.62	4280	4.79	2228	7.81	4.640	0.595	11.77	168	45	55	29.016
50% of Pull at Maximum Power—Two Hours 85h (5PD) Gear											
38.44	2864	5.03	2282	5.29	3.876	0.706	9.92	167	40	46	28.985
50% of Pull at Reduced Engine Speed—Two Hours 12th (6DD) Gear											
38.32	2838	5.06	1430	5.29	2.840	0.519	13.50	166	44	54	29.010
MAXIMUM POWER IN SELECTED GEARS											
55.92	7779	2.70	2241	14.83	5th (3PD) Gear			169	33	36	29.270
63.62	6795	3.51	2098	13.90	7th (4PD) Gear			172	56	59	28.720
66.48	5702	4.37	2099	10.63	8th (5PD) Gear			174	53	62	28.790
67.95	4543	5.61	2100	8.07	10th (6PD) Gear			175	55	60	28.720
67.04	3405	7.38	2101	5.93	12th (6DD) Gear			174	54	60	28.710
66.78	2453	10.21	2101	4.42	13th (7PD) Gear			174	53	61	28.710

LUGGING ABILITY IN RATED GEAR (8th or 5PD)

Crankshaft Speed rpm	2099	1892	1681	1470	1254	1039
Pounds Pull	5702	6220	6658	6721	6368	5592
Increase in Pull %	0	9	17	18	12	-2
Horsepower	66.48	64.31	60.14	52.87	43.23	32.19
Miles Per Hour	4.37	3.88	3.39	2.95	2.55	2.16
Slip of Drivers %	10.63	12.08	13.42	13.90	12.81	10.95

TRACTOR SOUND LEVEL WITH CAB	dB(A)
Maximum Available Power 2 Hours	84.5
75% of Pull at Max. Power 10 Hours	85.0
50% of Pull at Max. Power 2 Hours	84.5
50% of Pull at Reduced Engine Speed 2 Hours	80.5
Bystander in 16th (8DD) gear	86.0

TIRES, BALLAST AND WEIGHT		With Ballast	Without Ballast
Rear Tires	—No., size, ply & psi	Two 18.4-34; 6; 16	Two 18.4-34; 6; 16
Ballast	—Liquid	1080 lb each	None
	Cast Iron	500 lb each	None
Front Tires	—No., size, ply & psi	Two 7.50-18; 6; 40	Two 7.50-18; 6; 40
Ballast	—Liquid	None	None
	Cast Iron	80 lb each	None
Height of drawbar		22.0 inches	22.0 inches
Static weight with operator—rear		8170 lb	5010 lb
	front	2590 lb	2430 lb
	total	10760 lb	7440 lb

Department of Agricultural Engineering
Dates of Test: September 22 to October 8, 1976
Manufacturer: Ford Motor Company, Tractor Operations, 2500 East Maple Rd., Troy, Michigan 48084

FUEL, OIL AND TIME **Fuel** Diesel No. 2 **Cetane No.** 51.8 (rating taken from oil company's typical inspection data) **Specific gravity converted to 60°/60°** 0.8406 **Fuel weight** 6.999 lbs/gal **Oil** SAE 30 API service classification SB/SE CA/CD **To motor** 1.950 gal **Drained from motor** 1.435 gal **Transmission and final drive lubricant** Ford M-2C53A **Total time engine was operated** 51 hours.

ENGINE: **Make** Ford **Type** 4 cylinder vertical diesel **Serial No.** *F080815* **Crankshaft** mounted lengthwise **Rated rpm** 2100 **Bore and stroke** 4.4" x 4.2" **Compression ratio** 15.6 to 1 **Displacement** 255 cu in **Cranking system** 12 volt **Lubrication** pressure **Air cleaner** paper and felt elements with centrifugal precleaner and dust evacuator **Oil filter** cotton blend screw-on cartridge **Oil cooler** engine coolant heat exchanger for crankcase oil, radiator for hydraulic and transmission oil **Fuel filter** nylon gauze in bottom of tank and paper element **Muffler** vertical **Cooling medium temperature control** thermostat.

CHASSIS **Type** standard **Serial No.** C510283 **Tread width** rear 56" to 80" front 52" to 80" **Wheel base** 87.5" **Center of gravity** (without operator or ballast, with minimum tread, with fuel tank filled and tractor serviced for operation) Horizontal distance forward from center-line of rear wheels 28.6" Vertical distance above roadway 39.9" Horizontal distance from center of rear wheel tread 0" to the right/left **Hydraulic control system** direct engine drive **Transmission** selective gear fixed ratio with partial (2 range) operator controlled power shift **Advertised speeds mph** first 1.2 second 1.4 third 1.5 fourth 1.9 fifth 2.5 sixth 3.2 seventh 3.5 eighth 4.2 ninth 4.5 tenth 5.2 eleventh 5.3 twelfth 6.7 thirteenth 9.1 fourteenth 11.7 fifteenth 12.5 sixteenth 16.1 reverse 1.7, 2.1, 5.8, 7.7 **Clutch** single plate dry disc operated by foot pedal **Brakes** multiple wet disc operated by two foot pedals which can be locked together **Steering** power assist **Turning radius** (on concrete surface with brake applied) right 120" left 120" (on concrete surface without brake) right 138" left 138" **Turning space diameter** (on concrete surface with brake applied) right 252" left 252" (on concrete surface without brake) right 291" left 291" **Belt pulley** 1072 rpm at 2050 engine rpm diameter 11" face 6.5" **Belt speed** 3087 fpm **Power take-off** 540 rpm at 1900 engine rpm and 1000 rpm at 2059 engine rpm.

REPAIRS AND ADJUSTMENTS: Alternator support bolt was found to be broken after pto tests. This was repaired and tests continued.

REMARKS: All test results were determined from observed data obtained in accordance with SAE and ASAE test code or official Nebraska test procedure. Temperature at injection pump inlet was 160°F. Six gears were chosen between 15% slip and 15 mph.

We, the undersigned, certify that this is a true and correct report of official Tractor Test 1225.

LOUIS I. LEVITICUS
Engineer-in-Charge

G. W. STEINBRUEGGE
W. E. SPLINTER
K. VON BARGEN
Board of Tractor Test Engineers

The Agricultural Experiment Station
Institute of Agriculture and Natural Resources
University of Nebraska—Lincoln
H. W. Ottoson, Director

The first statement that was used in the program was as shown below:

```
              $JOB
     1                  REAL NOLOAD
```

This statement made the variable NOLOAD a real value in Fortran.

```
     2          READ,GEAR,CSLIP,DBHP,ORGLWT,BLSTWT,CGRAVY,SOIL,NOLOAD,
               XHITCH,WB,SRAW,SFAW,RTIRE,FTIRE,STCASE,RWB,FWB
```

This statement was used to get all of the required input parameters for the program. GEAR was the variable that meant what gear the tractor was operating in and was chosen from the "Maximum Power in Selected Gears" section of the Nebraska Tractor Test. Fifth gear was chosen from the previous Nebraska Tractor Test and this value of 5 was put on the first data card.

CSLIP was the variable that stood for the value of slip that was recorded on the Nebraska Tractor Test on concrete in the gear selected above. The value that corresponded to fifth gear was 14.83% and .1483 was entered on the second data card.

DBHP was the variable that stood for the amount of draw-bar horsepower that was recorded on concrete in the gear selected above. The value that corresponded to fifth gear was 55.92 and was recorded on the third data card.

ORGLWT stood for the original weight of the tractor without ballast. This value was found at the bottom of the Nebraska Tractor Test and for the Ford 7600 Diesel it was 7440 and was recorded on the fourth data card.

BLSTWT stood for the ballasted weight of the tractor. This value was also found at the bottom of the Nebraska Tractor Test and its value for the Ford 7600 was 10760 and was recorded on the fifth data card.

CGRAVY stood for the center of gravity of the tractor in the y direction or the vertical direction. This value was also found on the Nebraska Tractor Test and its value was 39.9 and this value was recorded on the sixth data card.

SOIL was the soil type the tractor was operating in. The choices that were used for the different soils were 2, which stood for firm soil, 3, which stood for tilled soil, and 4, which stood for sandy soil. The user of the program could choose to use 2, 3, or 4. The value that was used for the Ford 7600 was 2, firm soil, and 2 was recorded on the seventh data card.

NOLOAD was the advertised speed of the tractor in the gear chosen above and was found in the Nebraska Tractor Test. For the Ford 7600 in 5th gear, the advertised speed was 2.5 miles per hour and 2.5 was recorded on the eighth data card.

HITCH stood for the hitch type the tractor was operating with. The choices that were available in this program were 1, which was an integral hitch, 2, which was a semi-integral hitch, and 3, which stood for a towed hitch. The user could choose 1, 2, or 3, and an integral hitch, or 1, was chosen for the Ford 7600 and 1 was recorded on the ninth data card.

WB stood for the wheelbase of the tractor and was also found on the Nebraska Tractor Test. For the Ford 7600, the wheelbase was 87.5 and 87.5 was recorded on the tenth data card.

SRAW was the static rear axle weight for the ballasted tractor and was found from the Nebraska Tractor Test. For the Ford 7600, the SRAW was 8170 and 8170 was recorded on the eleventh data card.

SFAW was the static front axle weight for the ballasted tractor and was also found from the Nebraska Tractor Test. For the Ford 7600, the SFAW was 2590 and 2590 was recorded on the twelfth data card.

RTIRE stood for the rear tire size and was found from the Nebraska Tractor Test. The tire size was entered without any semi-colons or dashes in it and only the first numbers up to the first semi-colon were used so it was just a number. For the Ford 7600, the rear tire size was 18.4-34;6;16 so the number 18434 was entered on the thirteenth data card.

FTIRE stood for the front tire size and was found from the Nebraska Tractor Test. It was also entered exactly the same way as the rear tire above. For the Ford 7600, the front tire size was 7.50-18;6;40 so the number 75018 was entered on the fourteenth data card.

STCASE was the variable that accounted for "suitcase" weights on the front of the tractor. The type of ballast used was on the Nebraska Tractor Test. If there were no suitcase weights, the value of SUITCS equalled zero and for the Ford 7600 this was the case and 0 was entered on the fifteenth data card. If there was suitcase weights, the user would have to go out and measure the vertical distance from the center of the front axle to the center of gravity of the suitcase weights and record this value in inches on the fifteenth data card.

RWB was the rear weight ballast, or the total ballast added to the rear of the tractor found from the Nebraska Tractor Test. For the Ford 7600, 1080 pounds of liquid ballast and 500 pounds of cast iron was added to each tire. The total ballast added to the rear was then 3160 and 3160 was recorded on the sixteenth data card.

FWB was the front weight ballast and was found in the same way as the RWB. For the Ford 7600, 80 pounds of cast iron were added on each front wheel, so a total of 160 pounds was added so 160 was recorded on the seventeenth data card.

```
      PRINT80
   80 FORMAT(' ',3X,'GEAR',6X,'CSLIP',5X,'DBHP',5X,'ORGLWT',
     X4X,'BLSTWT',4X,'CGRAVY')
      PRINT81,GEAR,CSLIP,DBHP,ORGLWT,BLSTWT,CGRAVY
   81 FORMAT('0',4X,F3.0,5X,F5.2,5X,F6.2,4X,F6.0,4X,F6.0,4X,
     XF6.2)
      PRINT82
   82 FORMAT('-',3X,'SOIL',5X,'NOLOAD',4X,'HITCH',7X,'WB',
     X7X,'SRAW',6X,'SFAW')
      PRINT83,SOIL,NOLOAD,HITCH,WB,SRAW,SFAW
   83 FORMAT('0',4X,F3.0,5X,F5.2,7X,F3.0,5X,F6.2,4X,F6.0,
     X4X,F6.0)
      PRINT84
   84 FORMAT('-',2X,'RTIRE',5X,'FTIRE',5X,'STCASE',5X,
     X'RWB',7X,'FWB')
      PRINT85,RTIRE,FTIRE,STCASE,RWB,FWB
   85 FORMAT('0',1X,F7.0,3X,F7.0,3X,F7.2,4X,F6.0,4X,F6.0)
```

Statements number three through fourteen were simply format cards that instructed the computer to print out and label all of the input values it had received. The output caused by these statement could be seen at the end of the program.

```
15          IF(RTIRE.EQ.9516)RRADII=15.2
16          IF(RTIRE.EQ.184161)RRADII=19.5
17          IF(RTIRE.EQ.8324)RRADII=18.2
18          IF(RTIRE.EQ.9524)RRADII=19.0
19          IF(RTIRE.EQ.11224)RRADII=19.0
20          IF(RTIRE.EQ.12424)RRADII=20.8
21          IF(RTIRE.EQ.13624)RRADII=21.5
22          IF(RTIRE.EQ.14924)RRADII=22.4
23          IF(RTIRE.EQ.16924)RRADII=23.1
24          IF(RTIRE.EQ.13626)RRADII=22.6
25          IF(RTIRE.EQ.14926)RRADII=23.4
26          IF(RTIRE.EQ.16926)RRADII=24.1
27          IF(RTIRE.EQ.18426)RRADII=25.6
28          IF(RTIRE.EQ.23126)RRADII=27.7
29          IF(RTIRE.EQ.28126)RRADII=27.9
30          IF(RTIRE.EQ.11228)RRADII=21.9
31          IF(RTIRE.EQ.12428)RRADII=22.8
32          IF(RTIRE.EQ.13628)RRADII=23.5
33          IF(RTIRE.EQ.14928)RRADII=24.4
34          IF(RTIRE.EQ.16928)RRADII=25.1
35          IF(RTIRE.EQ.18428)RRADII=26.7
36          IF(RTIRE.EQ.14930)RRADII=25.5
37          IF(RTIRE.EQ.16930)RRADII=26.1
38          IF(RTIRE.EQ.18430)RRADII=27.4
39          IF(RTIRE.EQ.23130)RRADII=29.9
40          IF(RTIRE.EQ.24532)RRADII=31.5
41          IF(RTIRE.EQ.16934)RRADII=28.1
42          IF(RTIRE.EQ.18434)RRADII=29.4
43          IF(RTIRE.EQ.23134)RRADII=32.0
44          IF(RTIRE.EQ.13936)RRADII=26.9
45          IF(RTIRE.EQ.11238)RRADII=26.9
46          IF(RTIRE.EQ.13638)RRADII=28.6
47          IF(RTIRE.EQ.15538)RRADII=28.6
48          IF(RTIRE.EQ.16938)RRADII=30.4
49          IF(RTIRE.EQ.18438)RRADII=31.6
50          IF(RTIRE.EQ.20838)RRADII=32.8
51          IF(FTIRE.EQ.40012)FRADII=10.0
52          IF(FTIRE.EQ.60014)FRADII=12.5
53          IF(FTIRE.EQ.50015)FRADII=12.0

54          IF(FTIRE.EQ.7515)FRADII=13.6
55          IF(FTIRE.EQ.9515)FRADII=13.9
56          IF(FTIRE.EQ.1115)FRADII=14.4
57          IF(FTIRE.EQ.55016)FRADII=13.1
58          IF(FTIRE.EQ.60016)FRADII=13.5
59          IF(FTIRE.EQ.65016)FRADII=13.9
60          IF(FTIRE.EQ.75016)FRADII=14.7
61          IF(FTIRE.EQ.100016)FRADII=16.0
62          IF(FTIRE.EQ.110016)FRADII=17.3
63          IF(FTIRE.EQ.14161)FRADII=17.3
64          IF(FTIRE.EQ.75018)FRADII=15.9
65          IF(FTIRE.EQ.75020)FRADII=16.9
66          IF(FTIRE.EQ.95020)FRADII=17.9
```

Statement numbers fifteen through sixty-six were "if" statements that matched the front and rear tire sizes up with the appropriate static loaded radii. This part of the program was set up so that the user would only need the Nebraska Tractor Test to use the program and he would not have to waste time and effort searching for a table of static loaded radii. RRADII was the rear static loaded radius and FRADII was the front static radius.

```
67           PRINT86
68        86 FORMAT('-',2X,'RRADII',4X,'FRADII')
69           PRINT87,RRADII,FRADII
70        87 FORMAT('0',2X,F6.2,4X,F6.2)
```

Statement numbers sixty-seven through seventy were simply format statements that printed the labels and the values of the rear tire radius, RRADII, and the front tire radius, FRADII. The result of these statements could be seen at the end of the program.

```
      C    NOW NEED TO CALCULATE CENTER OF GRAVITY WITH BALLAST
71           BCTGRX=SFAW*WB/BLSTWT
72           BCTGRY=(CGRAVY*ORGLWT+RWB*RRADII+FWB*(FRADII+STCASE))/
          X(ORGLWT+RWB+FWB)
```

Statement numbers seventy-one through seventy-two calculated the ballasted center of gravity. BCTGRX was the ballasted center of gravity in the x direction, or the horizontal direction. It was measured in the same way as in the Nebraska Tractor Test; from the center of the rear axle to the center of gravity. BCTGRY was the ballasted center of gravity in the y direction, or the vertical direction. It was also measured in the same way as in the Nebraska Tractor Test; from the roadway to the center of gravity.

```
73               PRINT88
74            88 FORMAT('-',2X,'BCTGRX',4X,'BCTGRY')
75               PRINT89,BCTGRX,BCTGRY
76            89 FORMAT('0',2X,F6.2,4X,F6.2)
```

Statement numbers seventy-three through seventy-six were simply format statements that labelled and printed the values of the ballasted center of gravity.

```
           C    NOW WANT TO CALCULATE TRACTIVE EFFICIENCY
           C   TRACTIVE EFFICIENCY=DRAWBAR HORSEPOWER/AXLE HORSEPOWER
  77                AA=5.124
  78                BB=6.556
  79                CC=-1.596
  80                DD=-5.376
  81                EE=.6450
  82                SLIP=CSLIP
  83                TE=(-(AA*SLIP+CC)+SQRT((AA*SLIP+CC)**2-4*(BB*
                  XSLIP*SLIP+DD*SLIP+EE)))/2
```

Statement numbers seventy-seven through eighty-three calculated the tractive efficiency of the tractor on concrete during the Nebraska Tractor Test.

```
84          PRINT90
85       90 FORMAT('-',2X,'TRACTIVE EFFICIENCY ON CONCRETE')
86          PRINT91,TE
87       91 FORMAT('0',13X,F5.2)
```

Statement numbers eighty-four through eighty-seven were simply format statements that labelled and printed the value of TE, the tractive efficiency on concrete.

```
88              AHP=DBHP/TE
```

Statement number eighty-eight calculated the AHP, or the axle horsepower that the tractor had available.

```
89          PRINT92
90       92 FORMAT('-',2X,'AXLE HORSEPOWER')
91          PRINT93,AHP
92       93 FORMAT('0',6X,F6.2)
```

Statement numbers eighty-nine through ninety-two were simply format statements that labelled and printed the value of AHP, or axle horsepower.

```
                93              SLIP=.30
```

Statement number ninety-three initialized the value of slip that the tractor was operated in by the user to 30%.

```
 94          GO TO 10
 95       11 SLIP=SLIP-.01
 96       10 CONTINUE
 97          IF(SOIL.EQ.3)GO TO 12
 98          IF(SOIL.EQ.4)GO TO 13
 99          AA=6.928
100          BB=12.0
101          CC=-1.129
102          DD=-7.749
103          EE=.3895
104          TE=(-(AA*SLIP+CC)+SQRT((AA*SLIP+CC)**2-4*(BB*
            XSLIP*SLIP+DD*SLIP+EE)))/2
105          ALOADS=NOLOAD*(1-SLIP)
106          GO TO 14
107       12 CONTINUE

108          AA=6.928
109          BB=12.0
110          CC=-.7369
111          DD=-7.355
112          EE=.2375
113          TE=(-(AA*SLIP+CC)+SQRT((AA*SLIP+CC)**2-4*(BB*
            XSLIP*SLIP+DD*SLIP+EE)))/2
114          ALOADS=NOLOAD*(1-SLIP)
115          GO TO 15
116       13 CONTINUE
117          AA=8.
118          BB=16.
119          CC=-.228
120          DD=-8.772
121          EE=.1812
122          TE=(-(AA*SLIP+CC)+SQRT((AA*SLIP+CC)**2-4*(BB*
            XSLIP*SLIP+DD*SLIP+EE)))/2
123          ALOADS=NOLOAD*(1-SLIP)
124       14 CONTINUE
125       15 CONTINUE
```

Statement numbers ninety-four through 125 calculated TE, the tractive efficiency, and ALOADS, the actual travel speed, given the initial value of the slip and the soil type. This part of the program was broken up into three little blocks because there were three possible types of soil and tractive efficiency was dependent on the type of soil used. Statement numbers ninety-six through 107 were for firm soil, 108 through 116 were for tilled woil, and 117 through 125 were for sandy soil. Statement number ninety-five decreased the value of slip each time the route of the program was sent back through statement ninety-five.

```
126              IF(SOIL.EQ.2.AND.HITCH.EQ.1)GO TO 16
127              IF(SOIL.EQ.2.AND.HITCH.EQ.2)GO TO 17
128              IF(SOIL.EQ.2.AND.HITCH.EQ.3)GO TO 18
129              IF(SOIL.EQ.3.AND.HITCH.EQ.1)GO TO 19
130              IF(SOIL.EQ.3.AND.HITCH.EQ.2)GO TO 20
131              IF(SOIL.EQ.3.AND.HITCH.EQ.3)GO TO 21
132              IF(SOIL.EQ.4.AND.HITCH.EQ.1)GO TO 22
133              IF(SOIL.EQ.4.AND.HITCH.EQ.2)GO TO 23
134              IF(SOIL.EQ.4.AND.HITCH.EQ.3)GO TO 24
135           16 CONTINUE
136              AAA=.388
137              BBB=7.77
138              GO TO 25
139           17 CONTINUE
140              AAA=.333
141              BBB=8.23
142              GO TO 25
143           18 CONTINUE
144              AAA=.300
145              BBB=8.45
146              GO TO 25
147           19 CONTINUE
148              AAA=.348
149              BBB=6.31
150              GO TO 25
151           20 CONTINUE
152              AAA=.321
153              BBB=6.40
154              GO TO 25
155           21 CONTINUE
156              AAA=.322
157              BBB=5.69
158              GO TO 25
159           22 CONTINUE
160              AAA=.303
161              BBB=4.12
162              GO TO 25
163           23 CONTINUE
164              AAA=.313
165              BBB=3.62

166              GO TO 25
167           24 CONTINUE
168              AAA=.297
169              BBB=3.71
170           25 CONTINUE
171              DBPULL=BBB*SRAW*(AAA*AAA-(AAA-SLIP)**2)
```

Statement numbers 126 through 171 separated the operating conditions by soil type and hitch type, assigned the right constants to each condition for the drawbar pull equation, and then calculated the drawbar pull the tractor generated on the given soil and hitch type with the given value of slip.

```
172          DBHP=(DBPULL*ALOADS*5280)/(3600*550)
```

Statement number 172 calculated the DBHP, or the drawbar horsepower that the tractor would develop given the hitch type, soil type, and value of slip.

```
173          RQDAHP=DBHP/TE
```

Statement number 173 calculated the RQDAHP, or the required axle horsepower that was needed to power the tractor with the given value of slip.

```
174          IF(RQDAHP.GT.AHP)GO TO 11
```

Statement number 174 checked to see if the tractor had enough axle horsepower to meet the amount needed to operate at the given level of slip. If it did have it, the route continued through the program. If it did not have enough axle horsepower, the program was routed back to statement number ninety-five. Statement number ninety-five reduced the value of slip and all the calculations were made again. This process of lowering the slip was repeated until the tractor did have enough axle horsepower to operate with the given slip. Once it had enough axle horsepower, statement number 174 allowed the route to continue on through the program.

```
175           PRINT94
176        94 FORMAT('-',2X,'DBPULL',5X,'DBHP',5X,'RQDAHP',5X,'SLIP',
             X5X,'ALOADS',6X,'TE ON SOIL')
177           PRINT95,DBPULL,DBHP,RQDAHP,SLIP,ALOADS,TE
178        95 FORMAT('0',1X,F7.0,3X,F7.2,3X,F7.2,5X,F4.2,5X,F6.2,6X,F5.2)
```

Statement numbers 175 through 178 were simply format statements that labelled and printed the values of DBPULL, drawbar pull, DBHP, drawbar horsepower, RQDAHP, required axle horsepower, SLIP, slip on soil, ALOADS, actual travel speed, and TE on soil, tractive efficiency on soil.

```
179           IF(HITCH.EQ.1)DWC=.65
180           IF(HITCH.EQ.2)DWC=.45
181           IF(HITCH.EQ.3)DWC=.25
```

Statement numbers 179 through 181 assigned the values of DWC, the dynamic weight coefficient, depending on the hitch type that was used.

```
182              PRINT96
183           96 FORMAT('-',3X,'DWC')
184              PRINT97,DWC
185           97 FORMAT('-',2X,F4.2)
```

Statement numbers 182 through 185 were simply format statements that labelled and printed the value of DWC, the dynamic weight coefficient, that had been assigned for the given type of hitch.

```
186              H=0
```

Statement number 186 initialized H, the vertical height from the soil to the line of application of the total drawbar pull, to a value of zero which meant the line of pull passed through the surface of the ground(refer to drawings including the distance H).

```
187          DO 26 I=1,11
188          THETA=ATAN(DWC-H/WB)
189          THETAS=THETA*180/3.1415
190          PRINT58
191       58 FORMAT('-',2X,'     ')
192          PRINT59
193       59 FORMAT('-',2X,'      ')
194          PRINT98
195       98 FORMAT('1',4X,'H',7X,'THETAS')
196          PRINT99,H,THETAS
197       99 FORMAT('0',2X,F7.2,4X,F5.2)
198          PHI=0
199          DO 27 J=1,45
200          FWS=(BLSTWT*COS(PHI)*BCTGRX-BLSTWT*SIN(PHI)*BCTGRY)/WB
201          FWD=DBPULL*TAN(THETA)+FWS-DBPULL*DWC
202          PHIS=PHI*180/3.1415
203          PRINT70
204       70 FORMAT('-',3X,'FWS',7X,'FWD',7X,'PHIS')
205          PRINT71,FWS,FWD,PHIS
206       71 FORMAT('0',2X,F7.0,3X,F7.0,3X,F5.0)
207          PHI=PHI+3.1415*2/180
208          IF(FWD.LT.0)GO TO 50
209       27 CONTINUE
210       50 CONTINUE
211          H=H+RRADII/10.
212       26 CONTINUE
213          STOP
214          END
```

Statement numbers 187 through 214 checked the stability of the tractor. Statement 187 was the start of a "do loop" that incremented the distance H from 0 to the center of the rear axle. This meant that the line of pull kept being raised higher and higher up on the tractor. Statement number 199 started an "internal do loop" that incremented ϕ, the angle of inclination of the soil, in two degree increments up to the point where the FWD, the front weight dynamic, was equal to or less than zero. Since it was an "internal do loop", it incremented the slope of the soil from zero degrees to unstability for each increment of H. This allowed us to check not only the affects of ϕ, the angle of inclination of the soil, but also H, the height of the line of pull. Statements 188 and 189 calculated θ, the angle of pull for each increment. The way that this part of the program was set up meant that the output of the program would be such that for each value of H, θ was a constant and FWS and FWD were calculated for each two degree increment of ϕ. This method was very apparent after an examination of the form of the output. Whenever FWD, the front weight dynamic, equalled zero or was less than zero, this meant that the tractor was unstable.

Results

The main goal of this study was to come up with a mathematical model that would predict tractor stability. This goal was attained with the Fortran computer program that was shown in the previous section of this paper. Since it was not the goal of this study to actually study different models of tractors, only one tractor was used so the program could be tested. The one tractor that was used was a Ford 7600. The following results were obtained from the computer program using the Ford 7600 tractor with an integral hitch operating on firm soil:

```
      H           THETAS
        0.00      33.02

     FWS           FWD           PHIS
       2590.         2590.          0.

     FWS           FWD           PHIS
       2432.         2432.          2.

     FWS           FWD           PHIS
       2271.         2271.          4.

     FWS           FWD           PHIS
       2107.         2107.          6.

     FWS           FWD           PHIS
       1941.         1941.          8.

     FWS           FWD           PHIS
       1772.         1772.         10.
```

```
   FWS          FWD          PHIS
    1601.        1601.        12.

   FWS          FWD          PHIS
    1428.        1428.        14.

   FWS          FWD          PHIS
    1254.        1254.        16.

   FWS          FWD          PHIS
    1078.        1078.        18.

   FWS          FWD          PHIS
     900.         900.        20.

   FWS          FWD          PHIS
     722.         722.        22.

   FWS          FWD          PHIS
     543.         543.        24.

   FWS          FWD          PHIS
     363.         363.        26.

   FWS          FWD          PHIS
     182.         182.        28.

   FWS          FWD          PHIS
       1.           1.        30.

   FWS          FWD          PHIS
    -179.        -179.        32.
```

```
     H          THETAS
       2.94      31.65

    FWS          FWD           PHIS
     2590.        2310.           0.

    FWS          FWD           PHIS
     2432.        2151.           2.

    FWS          FWD           PHIS
     2271.        1990.           4.

    FWS          FWD           PHIS
     2107.        1827.           6.

    FWS          FWD           PHIS
     1941.        1660.           8.

    FWS          FWD           PHIS
     1772.        1492.          10.

    FWS          FWD           PHIS
     1601.        1321.          12.

    FWS          FWD           PHIS
     1428.        1148.          14.

    FWS          FWD           PHIS
     1254.         973.          16.

    FWS          FWD           PHIS
     1078.         797.          18.

    FWS          FWD           PHIS
      900.         620.          20.

    FWS          FWD           PHIS
      722.         441.          22.

    FWS          FWD           PHIS
      543.         262.          24.

    FWS          FWD           PHIS
      363.          82.          26.

    FWS          FWD           PHIS
      182.         -98.          28.
```

```
   H          THETAS
    5.88       30.23

  FWS          FWD          PHIS
   2590.        2029.         0.

  FWS          FWD          PHIS
   2432.        1871.         2.

  FWS          FWD          PHIS
   2271.        1710.         4.

  FWS          FWD          PHIS
   2107.        1546.         6.

  FWS          FWD          PHIS
   1941.        1380.         8.

  FWS          FWD          PHIS
   1772.        1211.        10.

  FWS          FWD          PHIS
   1601.        1040.        12.

  FWS          FWD          PHIS
   1428.         867.        14.

  FWS          FWD          PHIS
   1254.         693.        16.

  FWS          FWD          PHIS
   1078.         517.        18.

  FWS          FWD          PHIS
    900.         339.        20.

  FWS          FWD          PHIS
    722.         161.        22.

  FWS          FWD          PHIS
    543.         -18.        24.
```

```
     H            THETAS
      8.82     28.78

    FWS            FWD            PHIS
     2590.          1749.            0.

    FWS            FWD            PHIS
     2432.          1591.            2.

    FWS            FWD            PHIS
     2271.          1429.            4.

    FWS            FWD            PHIS
     2107.          1266.            6.

    FWS            FWD            PHIS
     1941.          1099.            8.

    FWS            FWD            PHIS
     1772.           931.           10.

    FWS            FWD            PHIS
     1601.           760.           12.

    FWS            FWD            PHIS
     1428.           587.           14.

    FWS            FWD            PHIS
     1254.           412.           16.

    FWS            FWD            PHIS
     1078.           236.           18.

    FWS            FWD            PHIS
      900.            59.           20.

    FWS            FWD            PHIS
      722.          -120.           22.
```

```
   H          THETAS
  11.76      27.28

  FWS          FWD          PHIS
   2590.        1468.          0.

  FWS          FWD          PHIS
   2432.        1310.          2.

  FWS          FWD          PHIS
   2271.        1149.          4.

  FWS          FWD          PHIS
   2107.         985.          6.

  FWS          FWD          PHIS
   1941.         819.          8.

  FWS          FWD          PHIS
   1772.         650.         10.

  FWS          FWD          PHIS
   1601.         479.         12.

  FWS          FWD          PHIS
   1428.         307.         14.

  FWS          FWD          PHIS
   1254.         132.         16.

  FWS          FWD          PHIS
   1078.         -44.         18.
   H          THETAS
   14.70      25.73

  FWS          FWD          PHIS
   2590.       1188.          0.

  FWS          FWD          PHIS
   2432.       1030.          2.

  FWS          FWD          PHIS
   2271.        869.          4.

  FWS          FWD          PHIS
   2107.        705.          6.

  FWS          FWD          PHIS
   1941.        538.          8.

  FWS          FWD          PHIS
   1772.        370.         10.

  FWS          FWD          PHIS
   1601.        199.         12.

  FWS          FWD          PHIS
   1428.         26.         14.

  FWS          FWD          PHIS
   1254.       -149.         16.
  H          THETAS
  17.64      24.15

 FWS         FWD          PHIS
  2590.        907.          0.

 FWS         FWD          PHIS
  2432.        749.          2.

 FWS         FWD          PHIS
  2271.        588.          4.

 FWS         FWD          PHIS
  2107.        424.          6.

 FWS         FWD          PHIS
  1941.        258.          8.

 FWS         FWD          PHIS
  1772.         89.         10.

 FWS         FWD          PHIS
  1601.        -82.         12.
```

```
     H           THETAS
     20.58       22.53

    FWS           FWD           PHIS
     2590.         627.           0.

    FWS           FWD           PHIS
     2432.         469.           2.

    FWS           FWD           PHIS
     2271.         308.           4.

    FWS           FWD           PHIS
     2107.         144.           6.

    FWS           FWD           PHIS
     1941.         -23.           8.
    H          THETAS
    23.52      20.87

   FWS          FWD          PHIS
    2590.        346.          0.

   FWS          FWD          PHIS
    2432.        188.          2.

   FWS          FWD          PHIS
    2271.         27.          4.

   FWS          FWD          PHIS
    2107.       -137.          6.
```

```
    H          THETAS
    26.46      19.17

   FWS          FWD          PHIS
    2590.         66.          0.

   FWS          FWD          PHIS
    2432.        -92.          2.
```

```
    H          THETAS
    29.40      17.43

   FWS          FWD          PHIS
    2590.       -215.          0.
```

Discussion of Results

One of the most interesting results of the computer program that used the Ford 7600 tractor was the affect of the raising of the line of pull, or increasing the distance H. When H was 0, the tractor reached instability at an angle of soil inclination of PHIS equal to 31°. When H was increased to 14.70 inches, approximately the halfway point from the ground to the center of the rear axle(29.4 inches), the tractor reached instability sooner at approximately 15° of soil inclination. When the pull was applied through the center of the rear axle, H equal to 29.4 inches, the tractor was unstable at 0° of soil slope. This affect of increasing instability with a higher line of pull clearly pointed out why designers try to keep the line of pull as low as possible.

Another interesting result was to examine the stability when H, the height of the line of pull, was approximately 6 inches above the surface of the soil. When H was equal to 5.88 inches, the tractor reached instability at a soil inclination angle of approximately 23°. This case where H was approximately 6 inches seemed to be rather close to an actual field situation where an integral hitch implement was being used and the line of pull would have been expected to have been approximately 6 inches high. The fact that the program predicted the tractor would be unstable at a ground slope of 23° seemed to be a reasonable answer. Since it was not possible to run any stability tests in an actual field situation with a tractor, the only way to get a "feeling" for a reasonable answer was to go by actual experience with operating tractors. 23° seemed like it was a practical solution and a "ballpark" figure for the amount of slope required to have the tractor reach instability. If the program had predicted a slope less than 10° or greater than 30°, it would have been questionable if the program was giving reasonable and practical predictions.

Conclusions

1. There were seventeen parameters that were needed to determine tractor stability in the analysis. These parameters were:

   1. The gear the tractor was operating in
   2. The drive wheel slip
   3. The drawbar horsepower the tractor developed
   4. The unballasted weight of the tractor
   5. The ballasted weight of the tractor
   6. The unballasted vertical center of gravity
   7. The soil type
   8. The advertised speed in the gear chosen
   9. The hitch type
   10. The wheelbase
   11. The ballasted rear axle weight
   12. The ballasted front axle weight
   13. The rear tire size
   14. The front tire size
   15. The location of suitcase weights
   16. The ballast added to the rear axle
   17. The ballast added to the front axle

2. It was possible to construct a mathematical model to predict tractor stability in the form of a computer program.

3. The best method of comparing various models of tractors was to use the Nebraska Tractor Test results.

4. The affect of the height of the line of pull was very significant. The higher the line of pull on the tractor, the less soil slope was required to tip the tractor.

Summary

The main goal of this study was to determine all of the parameters affecting longitudinal stability of tractors operating on slopes. This goal was accomplished by mathematically analyzing the tractor and using Hunt's equation of Zoz's traction chart. All of the mathematics involved in determining stability were then incorporated into a Fortran computer program. The program was written in such a manner that the user only needed a Nebraska Tractor Test to run the program. The main reason the Nebraska Tractor Tests were used was that they were an excellent means of comparing different models of tractors and they were readily available to almost any engineer. This program also allowed the user to select a wide range of operating conditions in that there were three hitch types to choose from and three soil types to choose from. This program could serve as an excellent tool to the implement and tractor designers as well as being an excellent means of studying the possibility of installing a mini-computer on the tractor that would instantaneously calculate stability and warn the operator when he was approaching instability with his tractor.

Recommendations for Further Study

As a result of this study, the following recommendations were made:

1. Actual field tests should be run in order to corollate the computer's predictions with the actual field results.
2. Studies should be made comparing the affects of hitch types and soil types on stability.
3. Studies should be made comparing the stability of various models(e.g. John Deere, International Harvester, Ford, Case, etc.) that were made in a given year.
4. Studies should be made comparing the stability of modern tractors with early tractors(e.g. 1977 John Deere vs. 1925 Ford).
5. Studies should be made of the technological and economical feasibility of using electronic sensing devices and a mini-computer that would instantaneously calculate the stability and somehow warn the operator.
6. Studies should be made and reviews of literature should be made to determine the magnitude and the location of the line of pull of many typical farm implements. These results should then be tried in the computer program.

Bibliography

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2. Hunt, D. R. , Class Notes for Agricultural Engineering 127, Agricultural Engineering Department, University of Illinois, Urbana, Illinois, 1976

3. Zoz, F. M. , "Predicting Tractor Field Performance", ASAE Paper #70-118, Presented at the 1970 Annual Meeting, Minneapolis, Minnesota, July 10, 1970

Appendix A

Instructions for Future Users of the Computer Program

This program was very simple to use and only required that the user have the Nebraska Tractor Test for the tractor he wanted to test. All the user had to do was to type up 17 separate data cards, one entry on each card, and insert them after the $ENTRY statement in the program. One number was entered on each card. Each number was started on column 7 and every number had to contain a period. The best way to explain how to find each number was to examine each card and use the Nebraska Tractor Test for the Ford Diesel 7600 on the following page to show where each number came from.

The first data card was for the gear the tractor was operating in. The user could choose any gear shown in the "Maximum Power in Selected Gears" section of the Nebraska Tractor Test. For the Ford tractor test, he could have chosen 5, 7, 8, 10, 12, or 13. Once a gear had been chosen, it was entered on the first data card. If 5th gear had been chosen, 5. would have been entered on the first data card starting in column 7.

The second data card was CSLIP, the slip recorded on concrete from the Nebraska Tractor Test. The slip value had to correspond with the same gear chosen above. If 5th gear had

NEBRASKA TRACTOR TEST 1225—FORD 7600 DIESEL 16-SPEED

POWER TAKE-OFF PERFORMANCE

Hp	Crankshaft speed rpm	Fuel Consumption Gal per hr	Fuel Consumption Lb per hp-hr	Hp-hr per gal	Temperature Degrees F Cooling medium	Temperature Degrees F Air wet bulb	Temperature Degrees F Air dry bulb	Barometer inches of Mercury
MAXIMUM POWER AND FUEL CONSUMPTION								
Rated Engine Speed—Two Hours (PTO Speed—1020 rpm)								
84.79	2100	5.399	0.446	15.70	199	60	75	28.890
Standard Power Take-off Speed (1000 rpm)—One Hour								
85.16	2059	5.338	0.439	15.95	200	62	75	28.870
VARYING POWER AND FUEL CONSUMPTION—Two Hours								
75.68	2204	5.118	0.473	14.79	196	62	75	.....
0.00	2334	1.659	.....	.....	176	61	75	.....
39.18	2282	3.463	0.619	11.31	178	58	76	.....
86.38	2100	5.521	0.447	15.65	204	60	76	.....
19.82	2310	2.542	0.897	7.80	174	60	75	.....
57.93	2249	4.286	0.518	13.52	182	60	75	.....
Av 46.50	2246	3.765	0.567	12.35	185	60	75	28.840

DRAWBAR PERFORMANCE

Hp	Drawbar pull lbs	Speed miles per hr	Crankshaft speed rpm	Slip of drivers %	Fuel Consumption Gal per hr	Fuel Consumption Lb per hp-hr	Hp-hr per gal	Temp Degrees F Cooling med	Temp Degrees F Air wet bulb	Temp Degrees F Air dry bulb	Barometer inches of Mercury
Maximum Available Power—Two Hours 8th (5PD) Gear											
65.33	5625	4.36	2100	10.98	5.251	0.563	12.44	176	54	62	28.810
75% of Pull at Maximum Power—Ten Hours 8th (5PD) Gear											
54.62	4280	4.79	2228	7.81	4.640	0.595	11.77	168	45	55	29.016
50% of Pull at Maximum Power—Two Hours 85h (5PD) Gear											
38.44	2864	5.03	2282	5.29	3.876	0.706	9.92	167	40	46	28.985
50% of Pull at Reduced Engine Speed—Two Hours 12th (6DD) Gear											
38.32	2838	5.06	1430	5.29	2.840	0.519	13.50	166	44	54	29.010
MAXIMUM POWER IN SELECTED GEARS											
55.92	7779	2.70	2241	14.83	5th (3PD) Gear			169	33	36	29.270
63.62	6795	3.51	2098	13.90	7th (4PD) Gear			172	56	59	28.720
66.48	5702	4.37	2099	10.63	8th (5PD) Gear			174	53	62	28.790
67.95	4543	5.61	2100	8.07	10th (6PD) Gear			175	55	60	28.720
67.04	3405	7.38	2101	5.93	12th (6DD) Gear			174	54	60	28.710
66.78	2453	10.21	2101	4.42	13th (7PD) Gear			174	53	61	28.710

LUGGING ABILITY IN RATED GEAR (8th or 5PD)

Crankshaft Speed rpm	2099	1892	1681	1470	1254	1039
Pounds Pull	5702	6220	6658	6721	6368	5592
Increase in Pull %	0	9	17	18	12	-2
Horsepower	66.48	64.31	60.14	52.87	43.23	32.19
Miles Per Hour	4.37	3.88	3.39	2.95	2.55	2.16
Slip of Drivers %	10.63	12.08	13.42	13.90	12.81	10.95

TRACTOR SOUND LEVEL WITH CAB	dB(A)
Maximum Available Power 2 Hours	84.5
75% of Pull at Max. Power 10 Hours	85.0
50% of Pull at Max. Power 2 Hours	84.5
50% of Pull at Reduced Engine Speed 2 Hours	80.5
Bystander in 16th (8DD) gear	86.0

TIRES, BALLAST AND WEIGHT		With Ballast	Without Ballast
Rear Tires	—No., size, ply & psi	Two 18.4-34; 6; 16	Two 18.4-34; 6; 16
Ballast	—Liquid	1080 lb each	None
	Cast Iron	500 lb each	None
Front Tires	—No., size, ply & psi	Two 7.50-18; 6; 40	Two 7.50-18; 6; 40
Ballast	—Liquid	None	None
	Cast Iron	80 lb each	None
Height of drawbar		22.0 inches	22.0 inches
Static weight with operator—rear		8170 lb	5010 lb
front		2590 lb	2430 lb

Department of Agricultural Engineering
Dates of Test: September 22 to October 8, 1976
Manufacturer: Ford Motor Company, Tractor Operations, 2500 East Maple Rd., Troy, Michigan 48084

FUEL, OIL AND TIME Fuel Diesel No. 2 Cetane No. 51.8 (rating taken from oil company's typical inspection data) Specific gravity converted to 60°/60° 0.8406 Fuel weight 6.999 lbs/gal Oil SAE 30 API service classification SB/SE CA/CD To motor 1.950 gal Drained from motor 1.435 gal Transmission and final drive lubricant Ford M-2C53A Total time engine was operated 51 hours.

ENGINE: Make Ford Type 4 cylinder vertical diesel Serial No. *F080815* Crankshaft mounted lengthwise Rated rpm 2100 Bore and stroke 4.4" x 4.2" Compression ratio 15.6 to 1 Displacement 255 cu in Cranking system 12 volt Lubrication pressure Air cleaner paper and felt elements with centrifugal precleaner and dust evacuator Oil filter cotton blend screw-on cartridge Oil cooler engine coolant heat exchanger for crankcase oil, radiator for hydraulic and transmission oil Fuel filter nylon gauze in bottom of tank and paper element Muffler vertical Cooling medium temperature control thermostat.

CHASSIS Type standard Serial No. C510283 Tread width rear 56" to 80" front 52" to 80" Wheel base 87.5" Center of gravity (without operator or ballast, with minimum tread, with fuel tank filled and tractor serviced for operation) Horizontal distance forward from center-line of rear wheels 28.6" Vertical distance above roadway 39.9" Horizontal distance from center of rear wheel tread 0" to the right/left Hydraulic control system direct engine drive Transmission selective gear fixed ratio with partial (2 range) operator controlled power shift Advertised speeds mph first 1.2 second 1.4 third 1.5 fourth 1.9 fifth 2.5 sixth 3.2 seventh 3.5 eighth 4.2 ninth 4.5 tenth 5.2 eleventh 5.3 twelfth 6.7 thirteenth 9.1 fourteenth 11.7 fifteenth 12.5 sixteenth 16.1 reverse 1.7, 2.1, 5.8, 7.7 Clutch single plate dry disc operated by foot pedal Brakes multiple wet disc operated by two foot pedals which can be locked together Steering power assist Turning radius (on concrete surface with brake applied) right 120" left 120" (on concrete surface without brake) right 138" left 138" Turning space diameter (on concrete surface with brake applied) right 252" left 252" (on concrete surface without brake) right 291" left 291" Belt pulley 1072 rpm at 2050 engine rpm diameter 11" face 6.5" Belt speed 3087 fpm Power take-off 540 rpm at 1900 engine rpm and 1000 rpm at 2059 engine rpm.

REPAIRS AND ADJUSTMENTS: Alternator support bolt was found to be broken after pto tests. This was repaired and tests continued.

REMARKS: All test results were determined from observed data obtained in accordance with SAE and ASAE test code or official Nebraska test procedure. Temperature at injection pump inlet was 160°F. Six gears were chosen between 15% slip and 15 mph.

We, the undersigned, certify that this is a true and correct report of official Tractor Test 1225.

LOUIS I. LEVITICUS
Engineer-in-Charge

G. W. STEINBRUEGGE
W. E. SPLINTER
K. VON BARGEN
Board of Tractor Test Engineers

The Agricultural Experiment Station
Institute of Agriculture and Natural Resources
University of Nebraska—Lincoln

been chosen, the slip was 14.83%. This value of slip was entered as a decimal value, so .1483 would have been entered on the second data card starting in column 7.

The third data card was DBHP, the drawbar horsepower recorded on concrete from the Nebraska Tractor Test. The DBHP value had to correspond with the same gear chosen above. If 5th gear had been chosen, the DBHP value was 55.92. This value of DBHP was entered as 55.92 on the third data card starting in column 7.

The fourth data card was ORGLWT, the unballasted weight of the tractor from the Nebraska Tractor Test. This value was found at the bottom of the Ford test and the value was 7440 pounds, so 7440. was entered on the fourth data card starting in column 7.

The fifth data card was BLSTWT, the ballasted weight of the tractor. This value was found at the bottom of the Ford test and the value was 10760 pounds, so 10760. was entered on the fifth data card starting in column 7.

The sixth data card was CGRAVY, the vertical center of gravity of the tractor. This value was also found from the Nebraska Tractor Test and for the Ford it was 39.90 inches, so 39.90 was entered on the sixth data card starting in column 7.

The seventh data card was SOIL, the soil type the user wanted the tractor to operate on. The user had a choice of 2, firm soil, 3, tilled soil, and 4, sandy soil. If firm soil was desired, 2. was entered on the seventh data card starting in column 7.

The eighth data card was NOLOAD, the advertised speed of the tractor in the gear chosen above. If 5th gear had been chosen, the advertised speed from the Nebraska Tractor Test was 2.5 mph, so 2.50 was entered on the eighth data card starting in column 7.

The ninth data card was HITCH, the hitch type the user wanted the tractor to operate with. The user had a choice of 1, integral hitch, 2, semi-integral hitch, or 3, towed hitch. If an integral hitch had been chosen, 1. would have been entered on the ninth data card starting in column 7.

The tenth data card was WB, the wheelbase of the tractor. This value was found from the Nebraska Tractor Test and for the Ford, 87.50 was entered on the tenth data card starting in column 7.

The eleventh data card was SRAW, the ballasted weight of the rear axle. This value was found from the Nebraska Tractor Test and for the Ford, 8170. was entered on the eleventh data card starting in column 7.

The twelfth data card was SFAW, the ballasted weight of the front axle. This value was found from the Nebraska Tractor Test and for the Ford, 2590. was entered on the twelfth data card starting in column 7.

The thirteenth data card was RTIRE, the rear tire size from the Nebraska Tractor Test. For the Ford, the rear tire size was 18.4-34. In order to enter this for the computer, all of the periods and dashes were taken out, so for the Ford, the RTIRE was equal to 18434, so 18434. was entered on the thirteenth data card starting in column 7. The user could check to see if he was entering the right form of the number by looking at the long list of "if" statements in the program for FTIRE and make sure that they matched.

The fourteenth data card was FTIRE, the front tire size from the Nebraska Tractor Test. For the Ford, the front tire size was 7.50-18. This number was entered in the same form as RTIRE. For the Ford, FTIRE was entered as 75018. on the fourteenth data card starting in column 7.

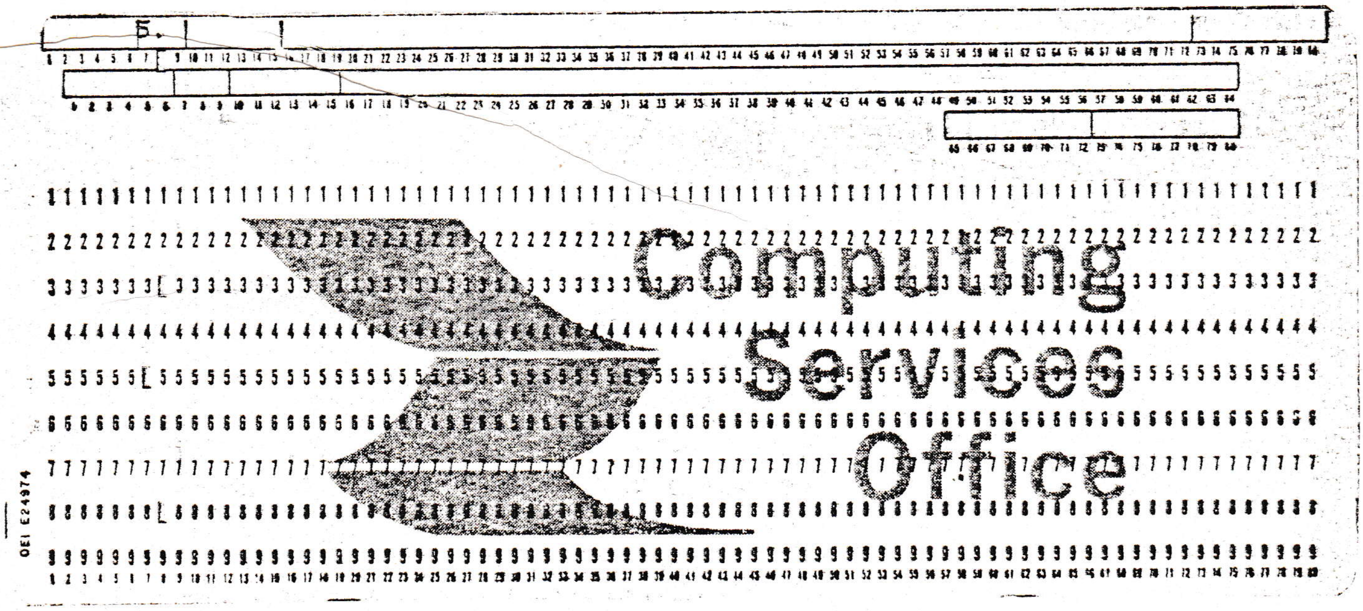
The fifteenth data card was STCASE, the vertical location of the center of gravity of suitcase weights if there were suitcase weights. If there were no suitcase weights as was the case of the Ford, 0. was entered on the fifteenth data card starting in column 7. If there were suitcase weights, the user would have had to go out and measure the vertical distance from the center of the front axle to the center of gravity of the suitcase weights in inches and enter this value on the fifteenth data card starting in column seven.

The sixteenth data card was RWB, the total ballast added to the rear axle from the Nebraska Tractor Test. For the Ford, 1080 pounds of liquid and 500 pounds of cast iron were added to each wheel, so the total ballast added to the rear axle was 3160 pounds. 3160. was entered on the sixteenth data card starting in column 7.

The seventeenth data card was FWB, the total ballast added to the front axle from the Nebraska Tractor Test. For the Ford, 80 pounds of cast iron were added to each wheel, so the total ballast added to the front axle was 160 pounds. 160. was entered on the seventeenth data card starting in column 7.

The following copy of the data cards used for the Ford 7600 with an integral hitch and operating on firm soil should help to show what a typical data deck looked like:

Card 1


5.

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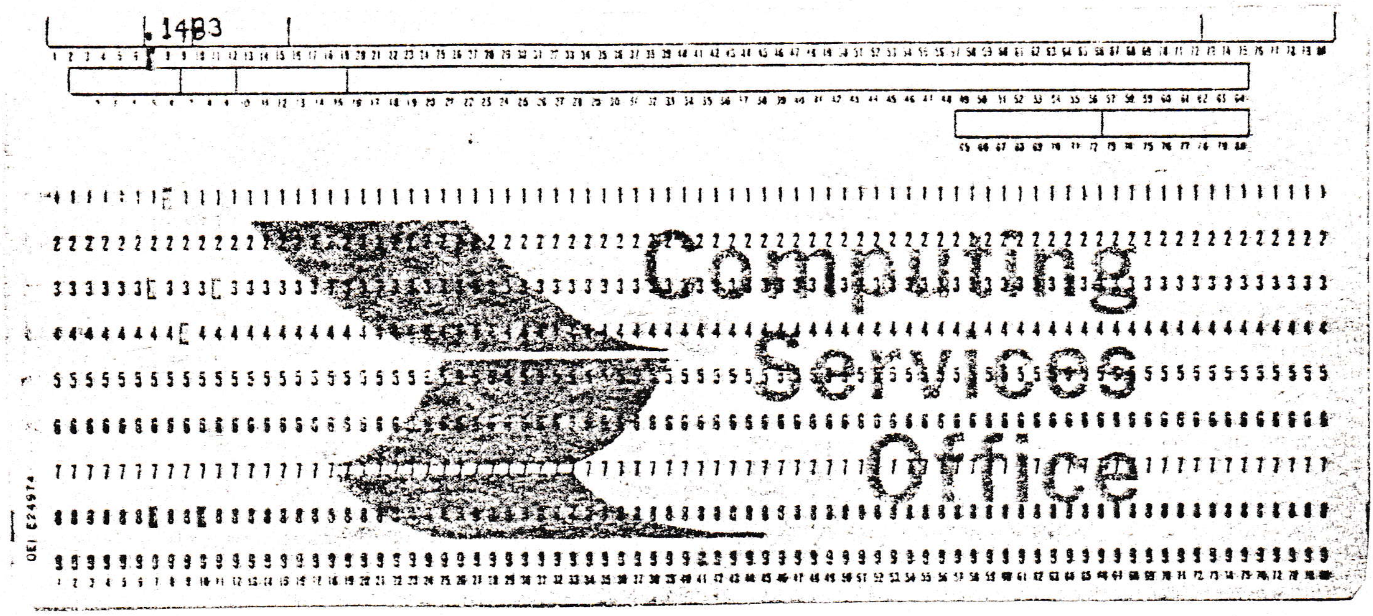
Card 2


.1483
Computing
Services
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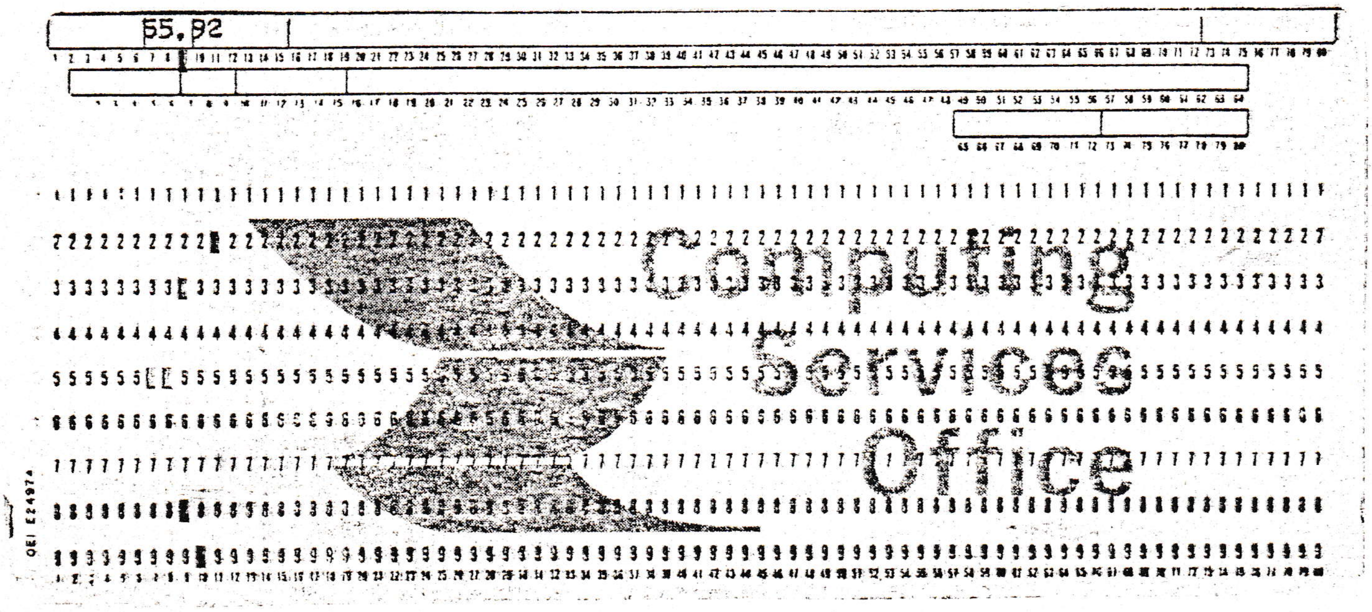
OEI E24974

Card 3


55.92
Computing
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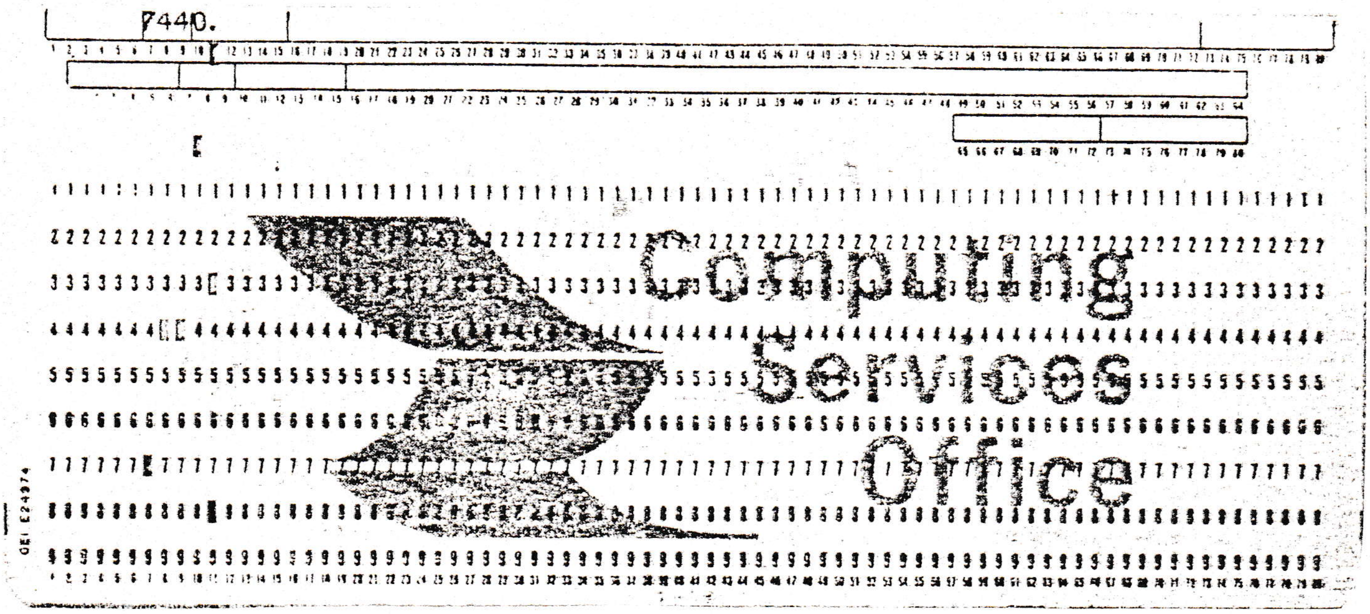
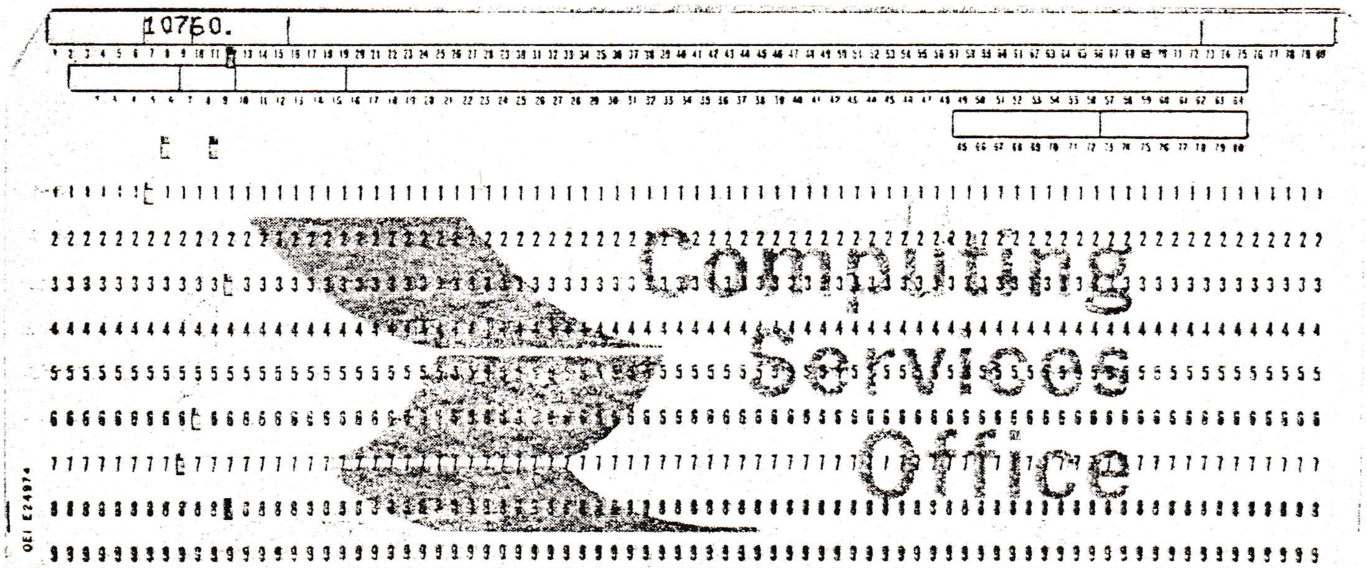
OEI E24974

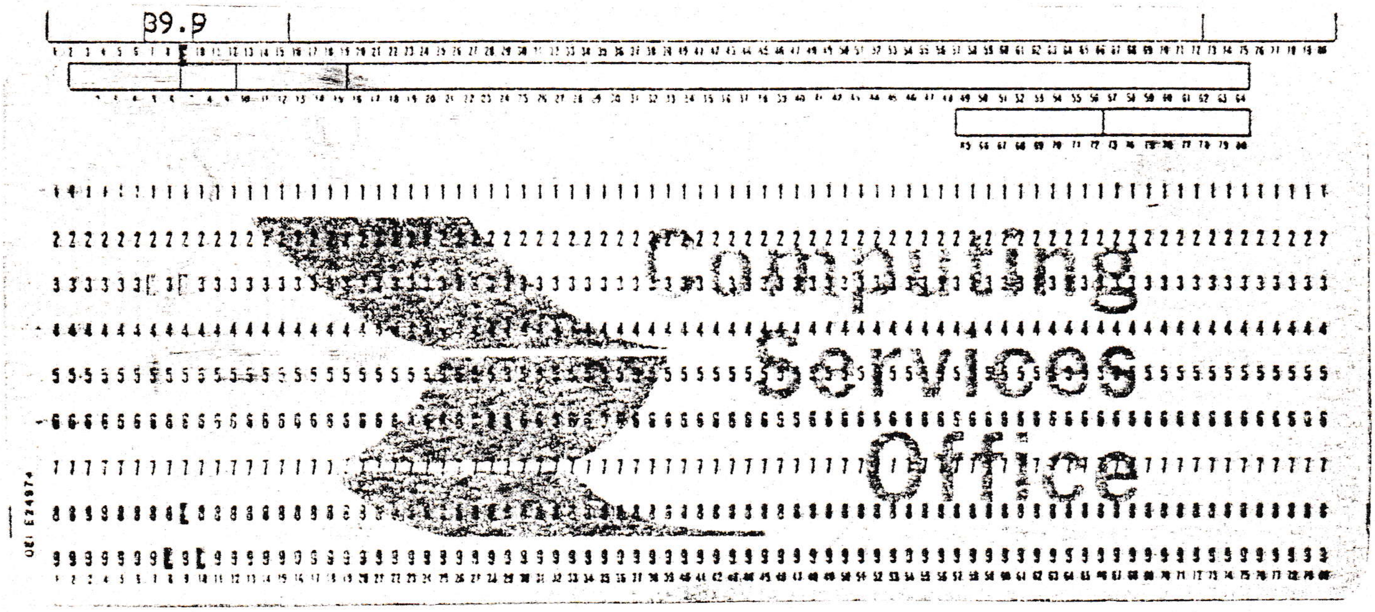
Card 4


7440.
Computing
Services
Office
QEI E24974

Card 5


10760.
Computing
Services
Office
QEI E24974

Card 6


39.9
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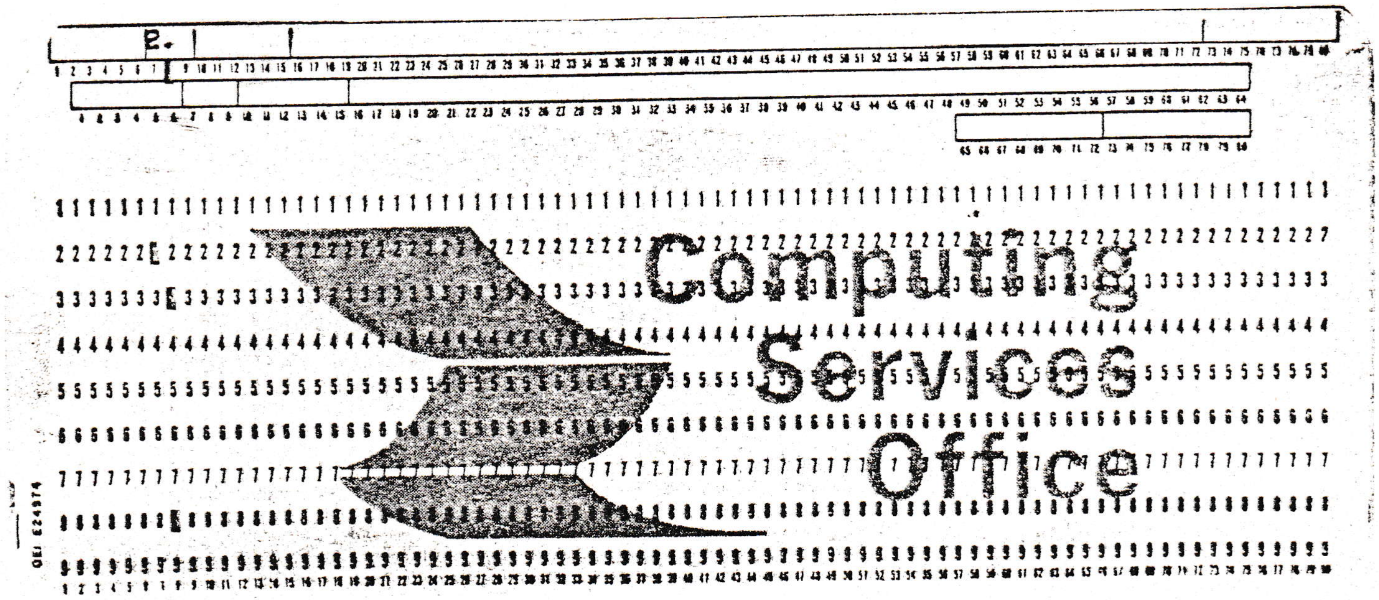
Card 7


2.
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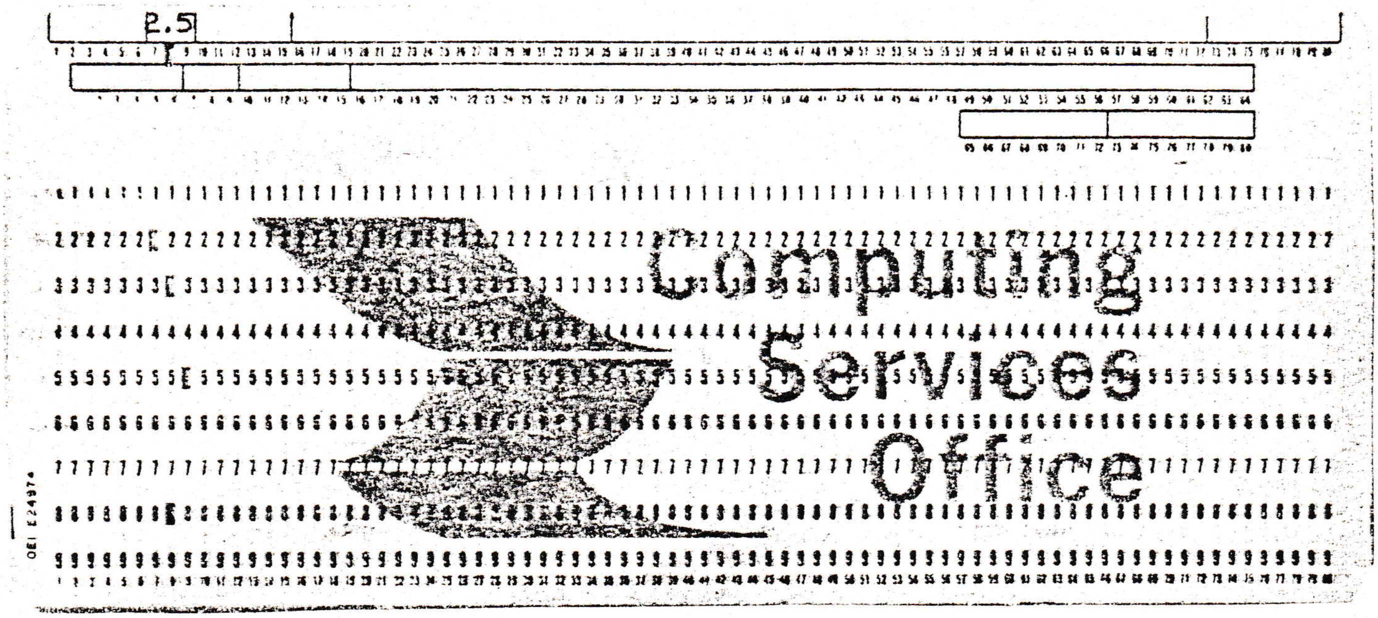
Card 8


2.5
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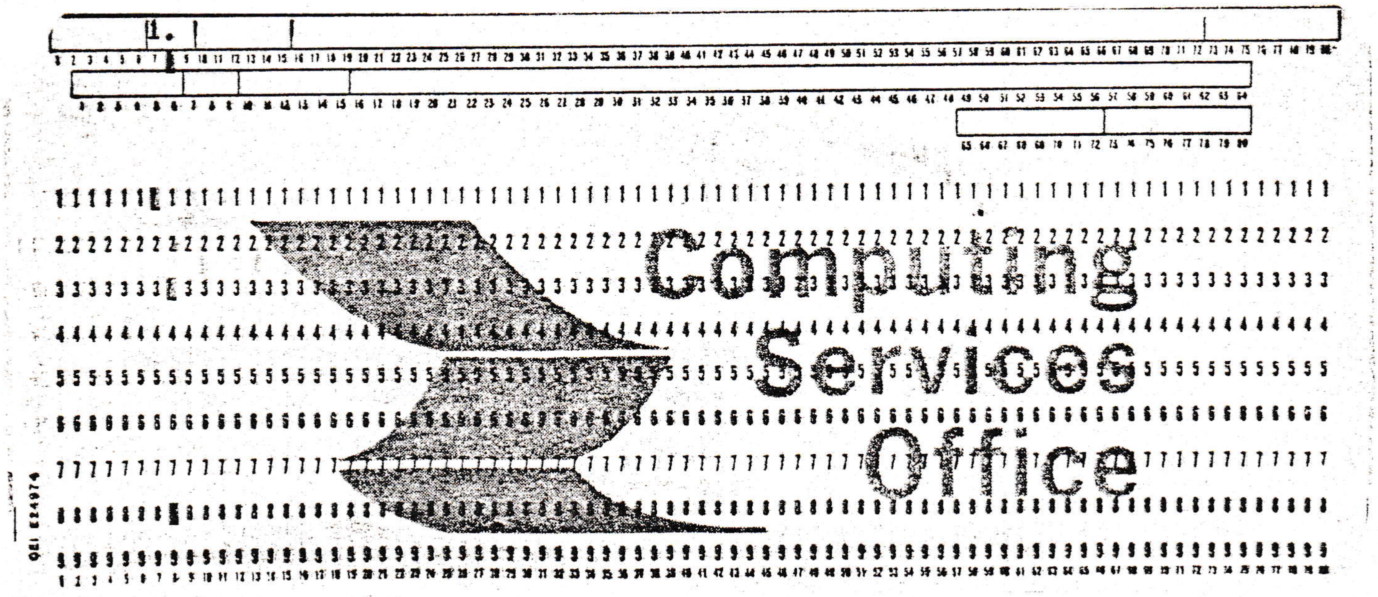
Card 9


1.
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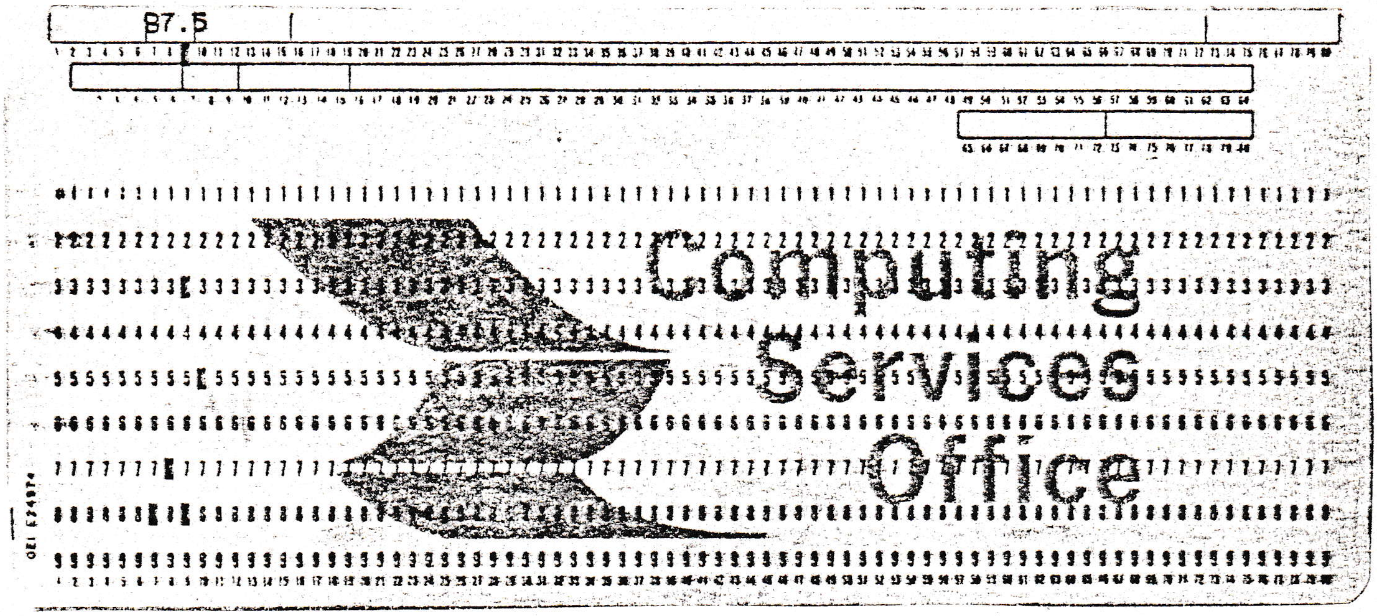
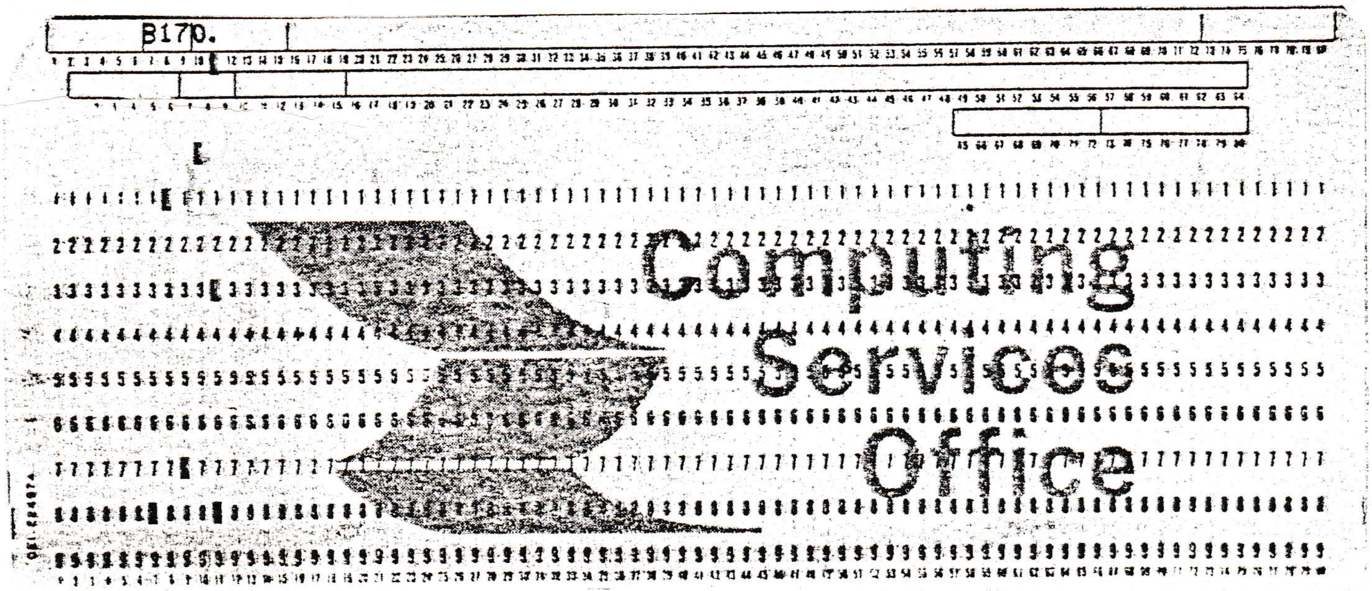
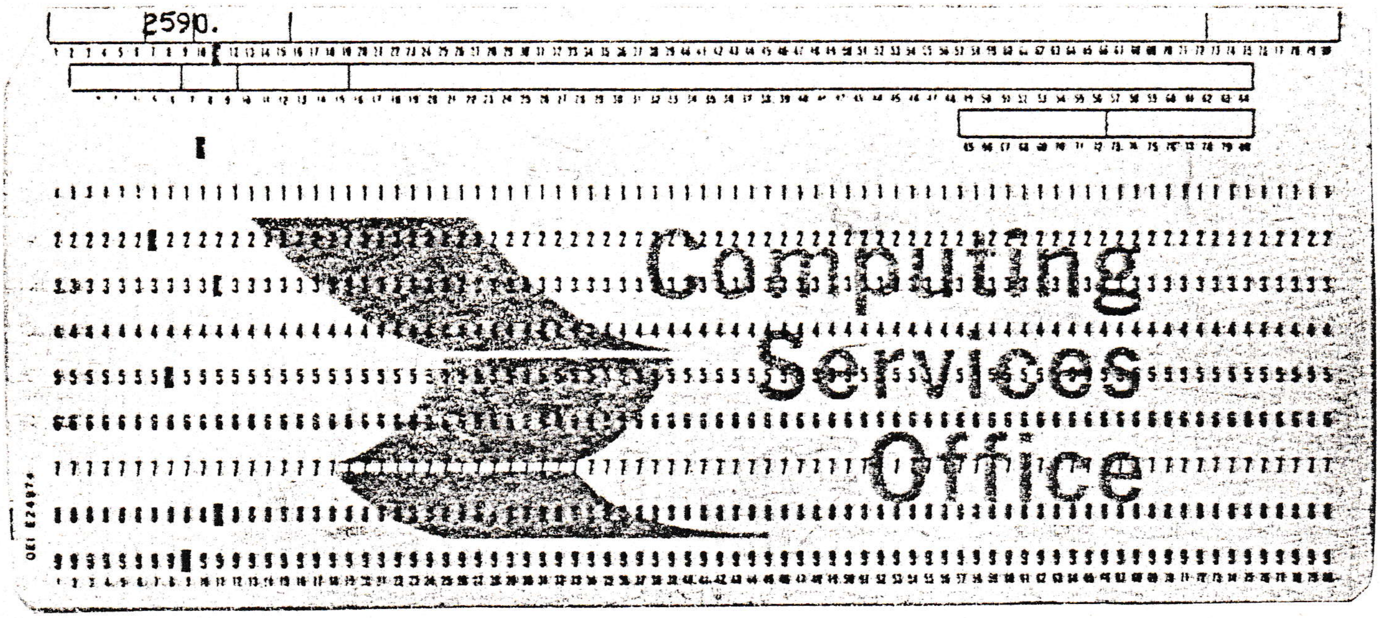
Card 10



Card 11



Card 12



2590.

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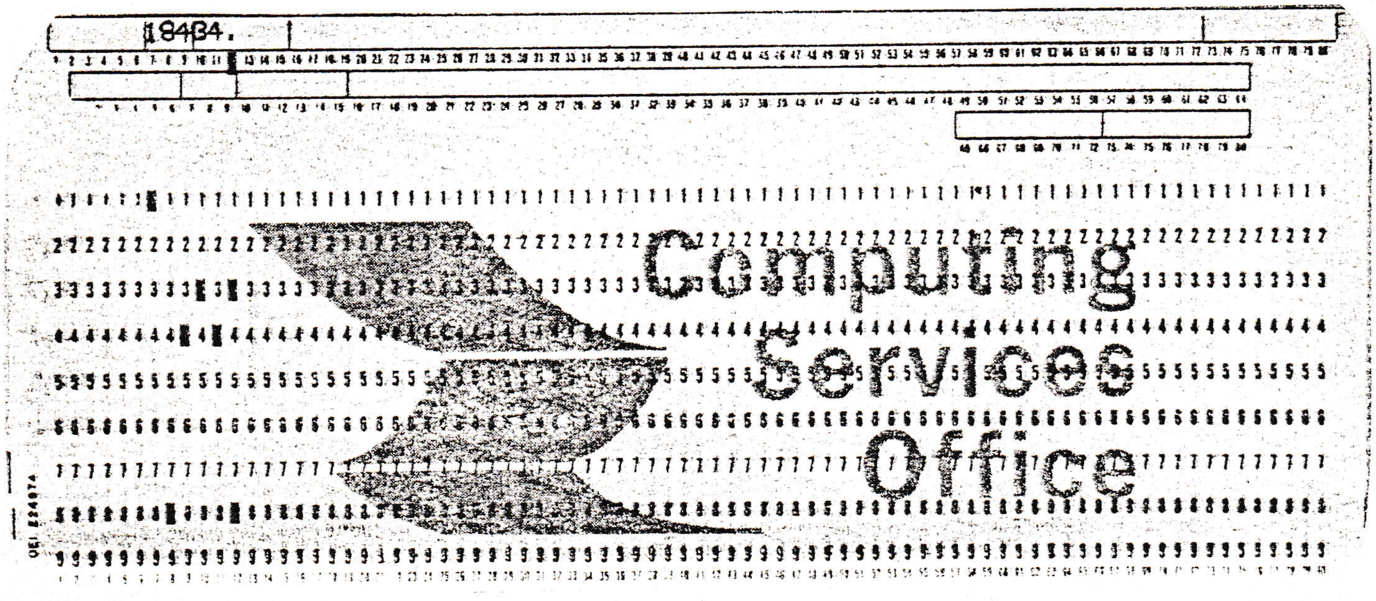
Card 13



18434.

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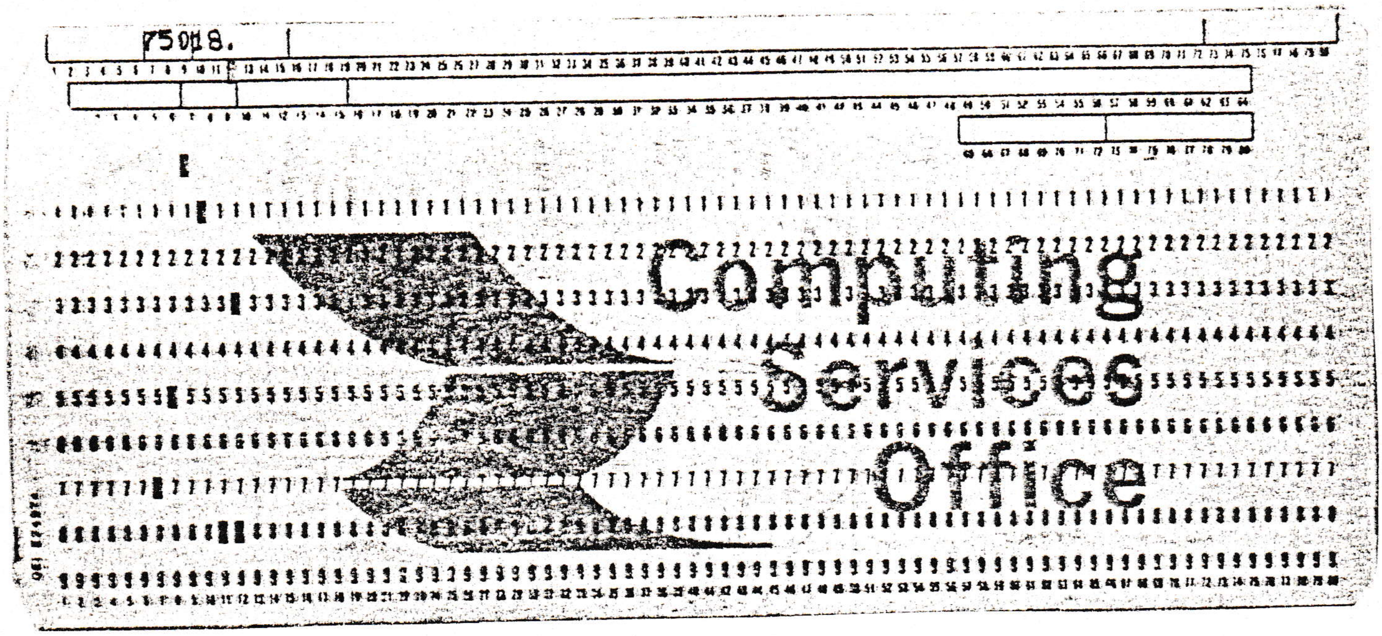
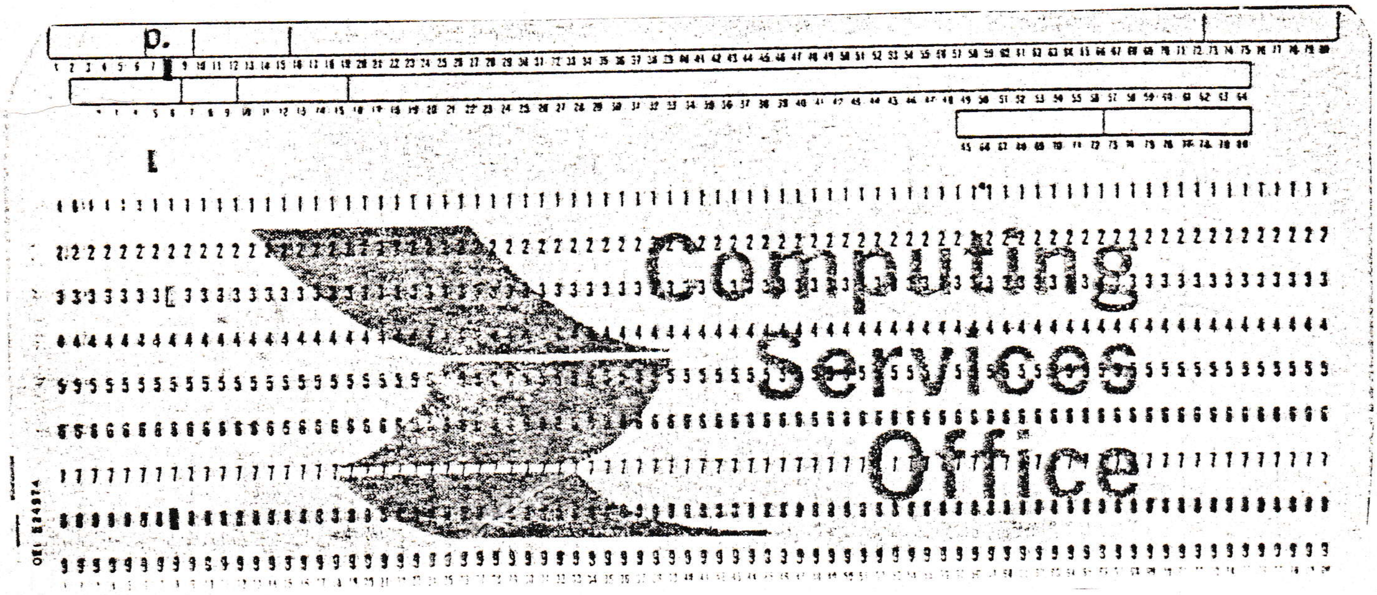
OEI E24874

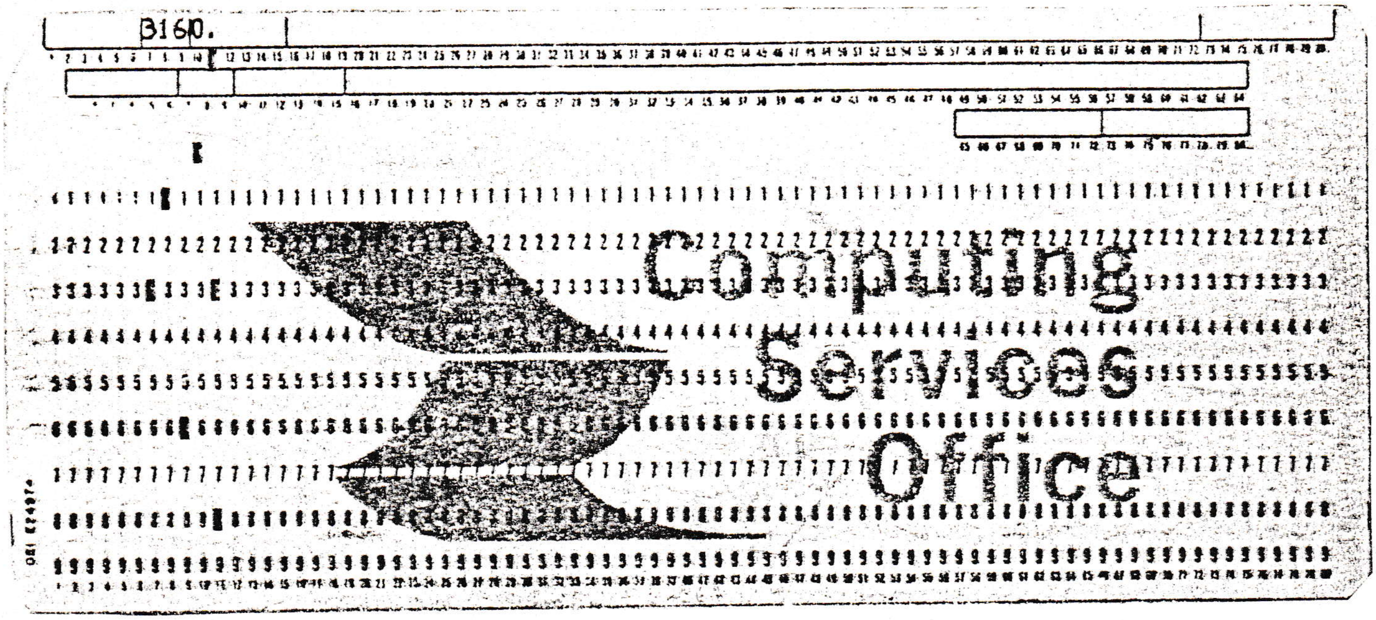
Card 14



Card 15

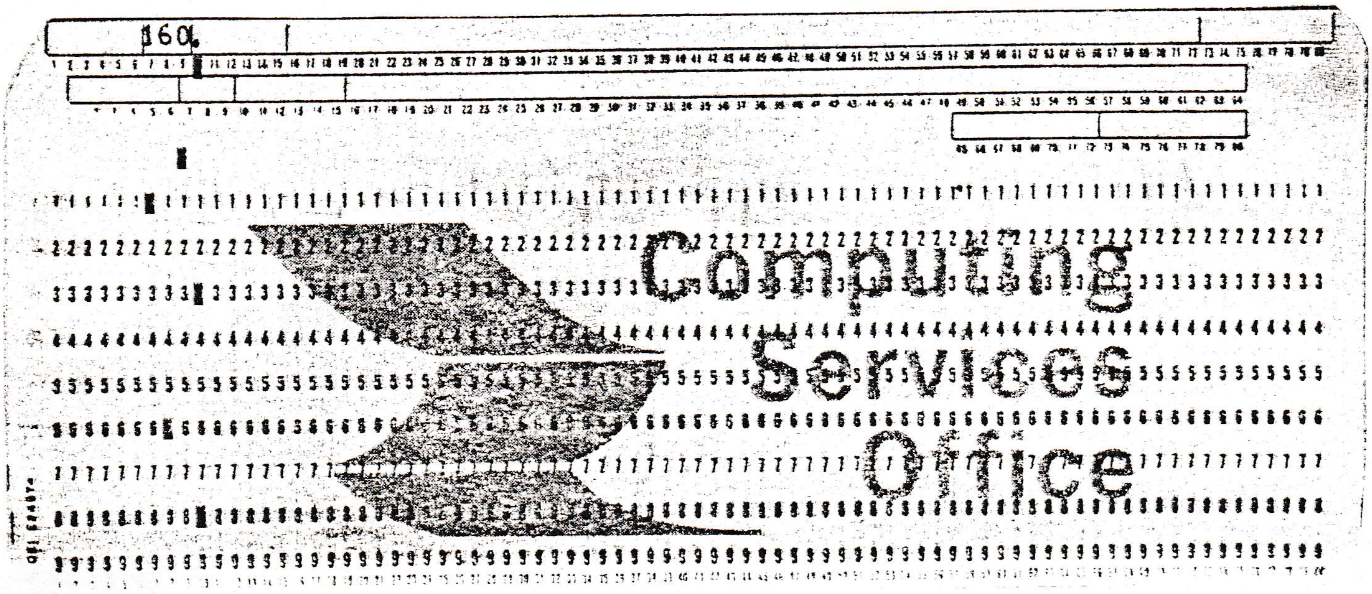


Card 16



B160.

Card 17



160.